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COMPOSITE-MATERIAL HELICOPTER ROTOR HUBS

B. Levenetz

Whittaker Corporation

Prepared for:

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July 1973

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COMPOSITE-MATERIAL
HELICOPTER ROTOR HUBS

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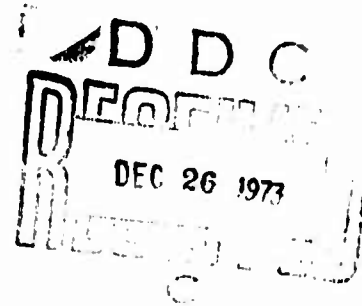
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U. S. ARMY AIR MOBILITY RESEARCH AND DEVELOPMENT LABORATORY
FORT EUSTIS, VIRGINIA

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WHITTAKER CORPORATION
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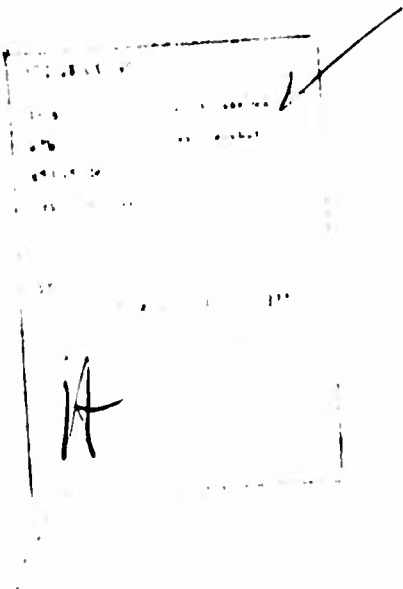SAN DIEGO, CALIFORNIA

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This report describes the development work conducted by the Whittaker Corporation
for construction of helicopter rotor hubs from fibrous composite materials.
The prototype hubs were designed to be structurally and functionally equivalent
to the metallic hub used on the Sikorsky CH-54B helicopter. The design is based
on the principle of filament-wound tension loops in combination with laminated
shear panels. The report contains a description of the design elements, of the
structural analysis, of the construction methods, and of the experimental evaluation
of rotor hubs subjected to static as well as cyclic loads. Design and construction
problems are discussed, and the potential of the composite hub concept is outlined.

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Helicopter						
Rotor Hubs						
Composite Material						
Glass Reinforced Plastics						
Filament-Winding						
Laminating						
Molding						
Adhesive Bonding						
Process Development						
Static Testing						
Fatigue Testing						
Composite Design						
Design Analysis						

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This program was performed under Contract DAAJ02-71-C-0032 with Whittaker Corporation, Research and Development Division.

The data contained in this report are the result of development work for design, construction, and test of a helicopter rotor hub made with fibrous composite materials. The hub is structurally and functionally equivalent to the metallic hub used on the CH-54B helicopter. Centrifugal forces are resisted by filament-wound symmetrical loops; vertical shear and torsion forces are resisted by a shear box made with glass cloth and cover plates made with *uni*directional glass material. Hub moment, vertical shear, and shaft output torque are reacted through a steel center core.

The report has been reviewed by the Eustis Directorate, U.S. A₁   Air Mobility Research and Development Laboratory, and is considered ₋o be technically sound. It is published for the exchange of information and the stimulation of future research.

The technical monitor for this contract was Mr. Arthur J. Gustafson, Technology Applications Division.

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COMPOSITE-MATERIAL
HELICOPTER ROTOR HUBS

Final Report

MJO 3027

By

B. Levenetz

Prepared by

Whittaker Corporation
Research and Development Division
San Diego, California

for

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ABSTRACT

This report describes the development work conducted by the Whittaker Corporation for construction of helicopter rotor hubs from fibrous composite materials. The prototype hubs were designed to be structurally and functionally equivalent to the metallic hub used on the Sikorsky CH-54B helicopter. The design is based on the principle of filament-wound tension loops in combination with laminated shear panels. The report contains a description of the design elements, of the structural analysis, of the construction methods, and of the experimental evaluation of rotor hubs subjected to static as well as cyclic loads. Design and construction problems are discussed, and the potential of the composite hub concept is outlined.

FOREWORD

This report was prepared by Whittaker Corporation, Research and Development Division, San Diego, California, under U. S. Army Contract DAAJ02-71-C-0032, "Composite Helicopter Rotor Hubs." The contract was administered by the Eustis Directorate, U. S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia, under the technical direction of Mr. A. Gustafson.

The report covers the contractual period from March 1971 to November 1972. Work at Whittaker Corporation was conducted under the direction of Mr. B. Levenetz, Manager of the Advanced Composites Engineering Department and Program Manager during the latter period of the program. Earlier Program Managers were Dr. J. Haener and Mr. A. Price. Other individuals who contributed significantly to the program were:

Mr. R. Anderson	- Structural design and liaison
Mr. A. Thompson	- Stress analysis
Dr. K. Berg	- Load analysis and experimental evaluation
Mr. J. Hilzinger	- Fabrication and quality control
Mr. C. Carlsen	- Selection of and coordination with vendors
Mr. D. McHargue	- Contract administration

Messrs. F. Campbell and J. Denham were responsible for fabrication and assembly of the composite hubs, and Mr. R. Tripp for testing.

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b	width, in.
F_{zs}	lift force on the rotor hub, lb
f_s	shear stress, $lb/in.^2$
I	moment of inertia, $in.^4$
M_c	in-plane moment, in.-lb
M_n	flapping moment, in.-lb
M.S.	structural margin of safety
P	applied load, lb
P_h	horizontal test load, lb
P_v	vertical test load, lb
$P_{(vector\ sum)}$	resultant of $P_h + P_v$
Q	static moment of a cross section, $in.^3$
Q_y	rotor hub torque moment, in.-lb
R	stress ratios
T_c	centrifugal force, lb
V_c	drag force, lb
V_n	lift force, lb
w/o	percent weight

INTRODUCTION

Fiber reinforced plastic composite materials have demonstrated their
potential as materials for structural components of high-performance
aircraft. Parts consisting of high-quality plastics reinforced with glass
fibers, boron fibers, or graphite fibers have been constructed and evalu-
ated under several Government-sponsored contracts. Properly designed
parts made from fibrous composite materials can be highly efficient com-
pared to their counterparts made from isotropic metallic materials. The
directional, anisotropic properties of these composites enable the designer
to adjust strength and stiffness by selecting the optimum fiber orientation
for a specific load condition. This makes it possible to control strength,
stiffness, and fatigue life at a minimum weight. All of the above-listed
fiber materials have very high specific tensile strengths, but they differ
significantly in specific stiffness, as well as cost; the glass fiber has
the lowest modulus compared with boron or high-quality graphite fiber, but
it is presently significantly less expensive than any of the so-called
"advanced fibers". The processing and handling methods for glass fibers
are also better established and less costly than those for the other two
types of fibers.

Fibrous composites are most efficient in applications where tension is the
predominant structural load. Therefore, pressure vessels, tension members,
or components subjected to high centrifugal forces offer the best potential
for achieving a high structural efficiency. Another advantage is seen in
replacing high-cost, strategic materials such as titanium and in avoiding
expensive tooling and machining operations of geometrically complex metal-
lic components. The helicopter rotor hub is one example where composite
materials could compete successfully with metals. Particularly large hubs,
such as required for heavy-lift helicopters, should result in weight- and
cost-efficient structures. The helicopter hub represents a component which
has to support very high tensile loads due to centrifugal forces and which
in the case of multiple blade rotors has a relatively complex geometry.
Therefore, it is particularly adaptable for application of fibrous composite
materials.

For a meaningful comparison of metallic and nonmetallic composite hubs, it
would be misleading to design a composite hub model which is optimized for
achieving the highest possible material utilization without consideration
of actual operational requirements and system details. Frequently specific
geometrical requirements, cutouts, attachments, or for composite materials,
unfavorable load components influence the design and may reduce the overall
efficiency of composite material utilization. Therefore, the U.S. Army has
selected for this program an operational rotor hub and has requested that
the composite hub be functionally identical to the existing metallic hub.
The selected hub is one which is used on the Sikorsky helicopter model
CH-54B. Its location in the main rotor head assembly is shown in Figure 1,
and the design of the metallic hub is indicated in Figure 2 (Sikorsky
Drawing No. 65103-11000). The subject development program of the composite

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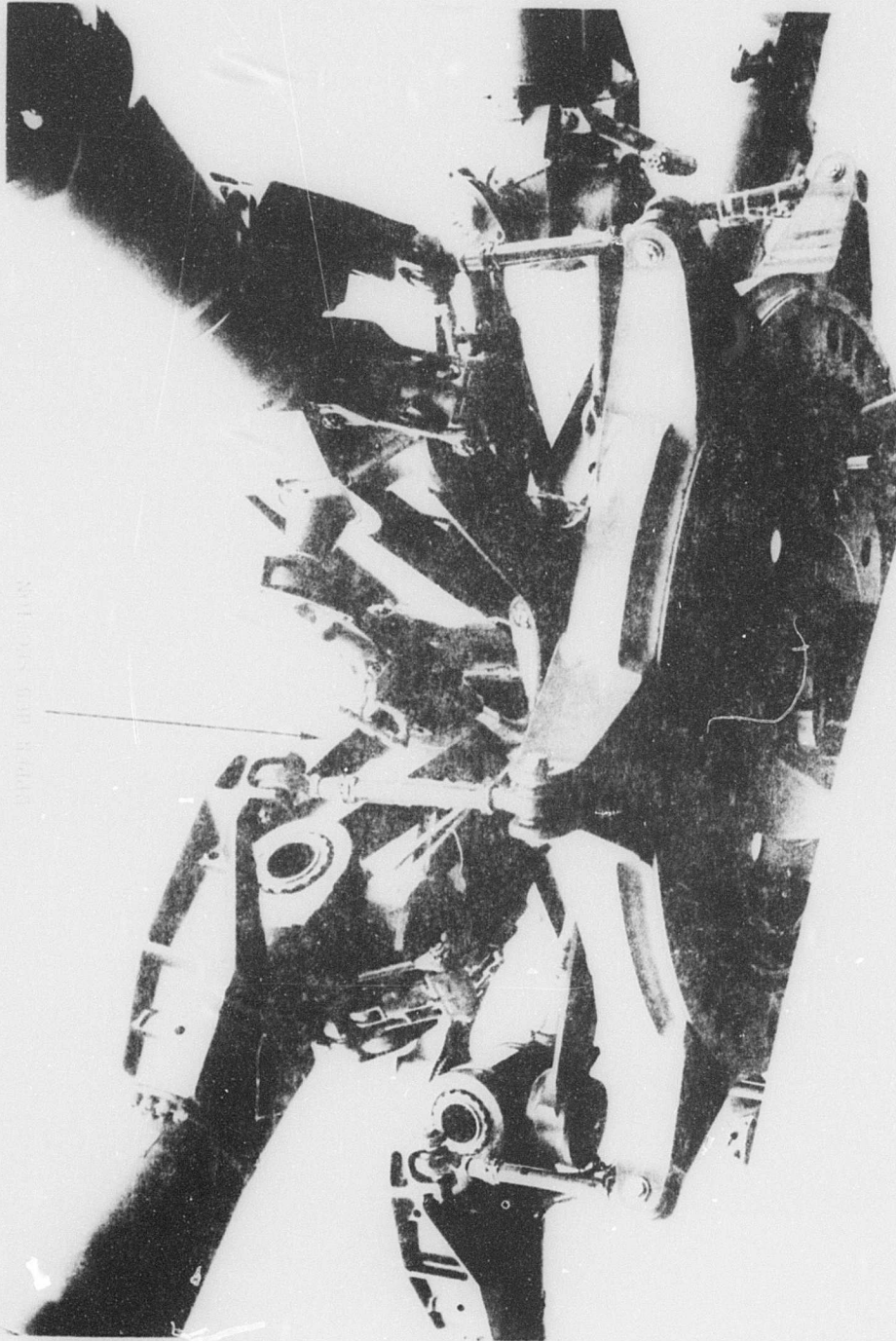
Figure 1. Rotor Head System of CH-54B.

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65103-11010-043 Main Rotor Hub

65103-11009-103 Lower Plate

65103-11021-043 Blade Hinge Assembly

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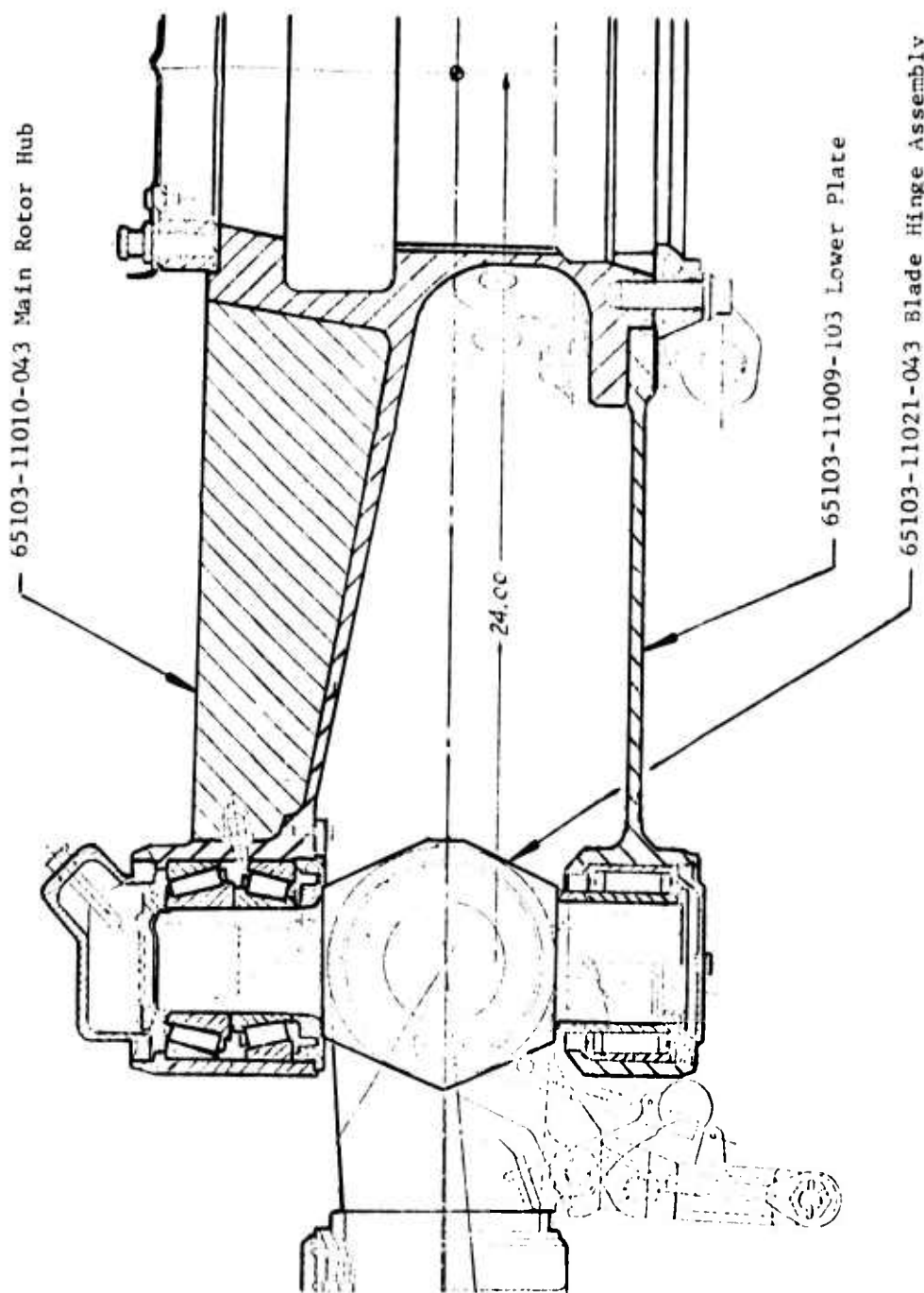
Figure 2. Metallic Hub Assembly.

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rotor hub is concentrated on the upper main section of the hub assembly,
which is represented by Sikorsky Part No. 65103-11010-043. The com-
posite hub should be structurally and functionally identical with the
present titanium hub, and interchangeable with respect to its attachment
to the rotor shaft, the lower plate (Sikorsky Part No. 65103-11009-103),
and blade hinge assembly (Sikorsky Part No. 65103-11021-043).

The scope of the program was:

- Design and structural analysis of the composite rotor hub by
  coordinating design and load requirements with Sikorsky Aircraft.

- Design and construction of tools adequate for fabrication of
  prototype hubs.

- Outline of a test plan by which the structural capability of the
  rotor hub can be experimentally evaluated.

- Design and construction of test fixtures.

- Fabrication of two rotor hub assemblies.

- Static testing of the first hub assembly.

- Cyclic testing of the second hub assembly.

- Preparation of monthly and final reports.

The program was completed in accordance with this scope with exception of
the test sequence.

TECHNICAL DISCUSSION

DESIGN ELEMENTS OF COMPOSITE HUB

Design Approach

The selected helicopter rotor hub carries six rotor blades and has there-fore six arms which are arranged at 60° spacing around a large central hub bearing that transmits the engine torque and lift forces to the rotor shaft. At the outer end of each arm is a bearing for the rotor blade hinge. The principal loads are acting on this hinge bearing in the following directions: radial (centrifugal) force, vertical (lift) force, and tangen-tial (drag) force. The largest static design load is in the radial direc-tion. The vertical static design load is approximately two-thirds of the radial load. The drag load is approximately 14% of the vertical load.

As a result of these load requirements, the design of the rotor hub arm is basically a cantilevered flexural beam which is also subjected to axial tension and some torque. The tension is held in equilibrium by *the* equal tension in the opposite arm. The vertical shear and bending load is counteracted by the central drive shaft. The basic design approach is shown in Figure 3. An exploded view without cover plates is presented in Figure 4. The detailed stress analysis is presented in Appendix I and the principal design assembly drawings are contained in Appendix II. The basic design elements are described in the following:

Loops

The centrifugal forces are resisted by filament-wound, elongated, symmetrical loops which take the tension loads, for fibrous materials, in a most advantageous manner. The structural cross section of the filament-wound unidirectional composite has a constant cross section of 0.075 inch. The cross section is rectangular but varies from 0.10 x 0.75 inch at the center of the loop to 0.19 x 0.40 inch at the hinge bearing. This causes the loop thickness to be slightly tapered. The fiber glass loop (page 227) contains aluminum insert plates in the center (0.10 inch thick) and at both ends (0.19 inch thick). Figure 5 shows one tension loop ready for assembly. Thirty-six loops are required for one hub assembly, or a package of 12 loops for one double arm (see Figure 4). The three packages are assembled sequen-tially interspersed at 60° spacing between each package. This results at the center in a nominal thickness of the interspersed packages of 0.10 x 36 = 3.60 inches, and at the hinge bearing of only 0.19 x 12 = 2.28 inches. The difference of 1.32 inches at the bearings is compensated for by eleven spacers (page 231), which are pressure molded from a glass fiber reinforced molding compound. These spacers have an outer contour identical to the loops, the same size inner cutout, and a nominal tapered thickness of 0.12 inch at the bearing and 0.10 inch at the hub center. The molded spacer is shown in Figures 4 and 6. In addition, other spacers (4676*p.219) are inserted

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* Whittaker part number listed on assembly drawing, Appendix II.
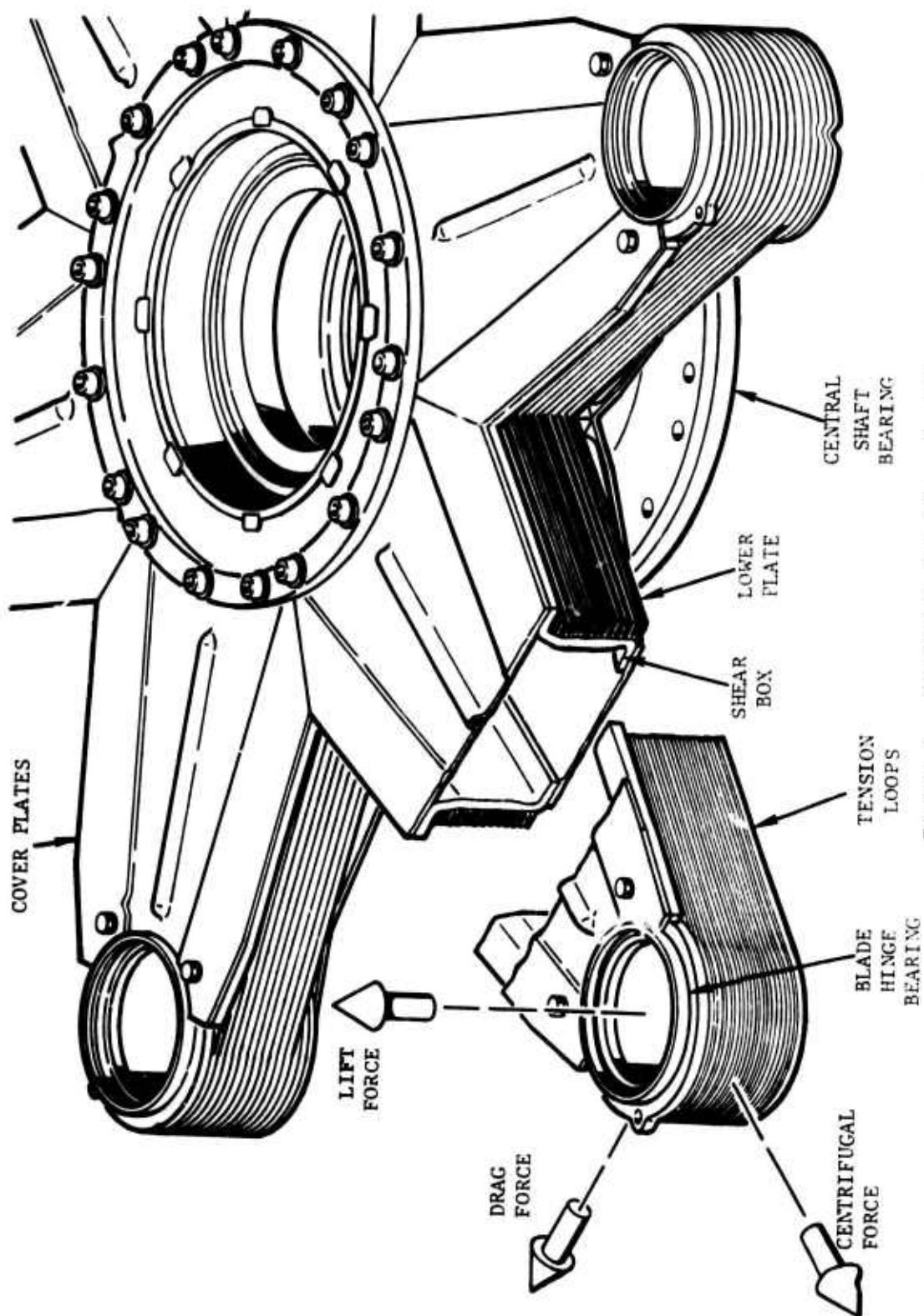
Figure 3. Composite Hub Elements (Shown on One Arm).

COVER PLATES

CENTRAL SHAFT BEARING

LOWER PLATE

SHEAR BOX

TENSION LOOPS

BLADE HINGE BEARING

LIFT FORCE

DRAG FORCE

CENTRIFUGAL FORCE

6

SHEAR BOX

LOOP

SPACER

SHEAR TAPE

BLADE HINGE BEARING

TENSION LOOP PACKAGE
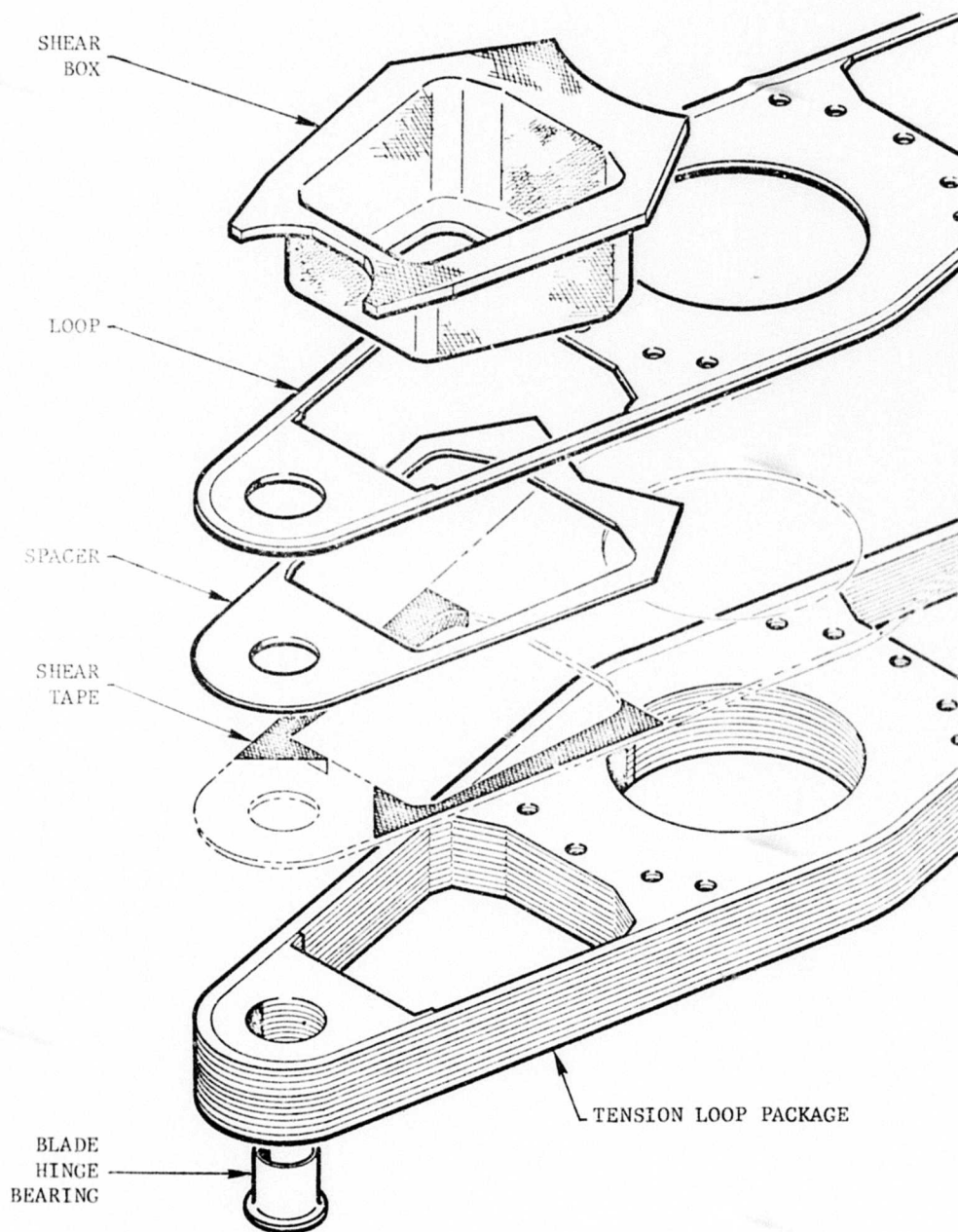
Figure 4. Hub Double Arm, Exploded View.

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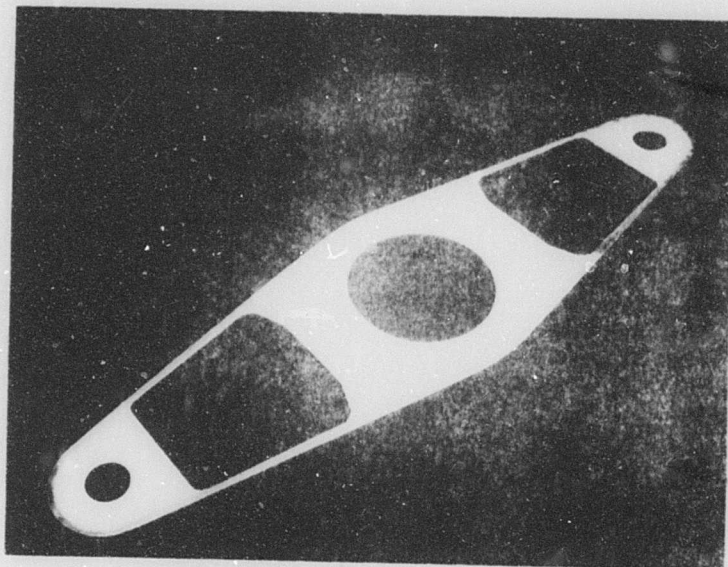
Figure 5. Tension Loop.
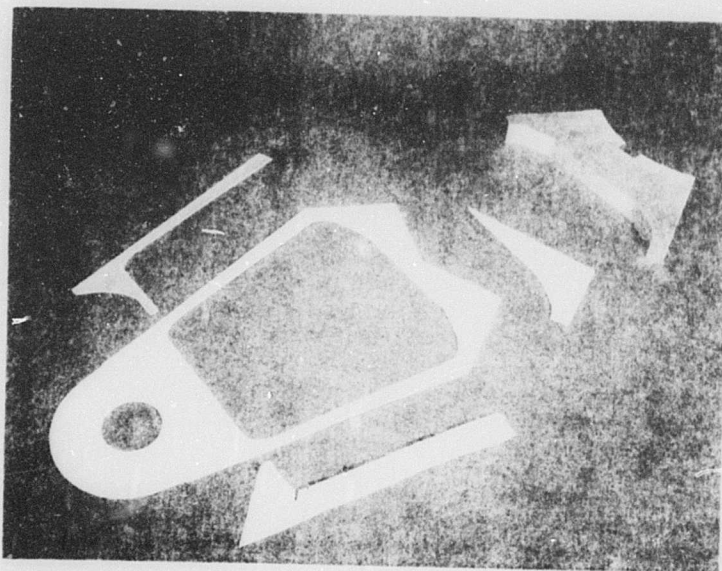
Figure 6. Spacers and Doublers.

with each set of loops to fill corners formed by the crossing loop
(see Figure 6). To compensate for the level variations caused by the
staggered loops at the upper reference surfaces of the hub assembly,
doublers (4707, p. 219) are bonded between the upper loops and the
flanges of the shear boxes (see Figure 6).

Shear Box

The bonded package of loops and spacers is capable of accepting the
full centrifugal tension level, but it is not sufficient to transmit
the full required bending shear load or any major torsional shear
load. The transfer of the required large shear load is accomplished
by a shear box which is laminated from woven glass fabric with a
fiber orientation approaching optimum for effective shear transfer
(-4, p. 219). The geometry of this shear box is shown in Figures 4
and 7. It is molded to final shape in a separate molding fixture.
During assembly operations of the hub, it is placed inside the tension
loops and the molded spacers. A reliable shear joint between the
loop package and the box is achieved by introduction of shear tapes
(-7, -8, -10, p.219). The tapes, which are cut at 45° fiber orientation,
are bent over the spacer edge and are bonded between the loops and
spacers as well as between the loop package and the shear box. Their
shape is indicated also in Figures 4 and 6.

Cover Plates

The beam box structure is completed by bonding the lower plate
(page 229) and the cover plates (-1, p. 219). These plates act as
caps of the beam section, transmitting tension and compressive loads
due to vertical shear, and also supplement the shear box structure
for transmitting torsional loads. The lower plate is designed as
a six-pronged star with a composed fiber orientation which is selected
to transmit axial as well as shear loads (see Figure 8). It is bonded
to the lower surface of the shear box, to the ring area around the hub
enter bearing, and to a portion of the loop area around the blade
hinge bearings. To compensate for the difference in loop package
thickness and shear box height at the hub shaft bearing, six spacers
(4677,p.219) are provided which are bonded to the lower plate and the
lower loop surfaces (see Figure 6). The six separate cover plates,
as shown also in Figure 8, at the upper surface of the hub are
designed to transmit axial and shear loads as well. They are bonded
to the flanges of the shear boxes and to the upper surfaces around
the bearings. The upper and lower plates are mechanically joined
together with the loop package by mounting bolts at the hub main
bearing and by tie bolts at the hinge bearing. This is done for
additional reliability to prevent development of peel forces when the
hub arms are subjected to large bending loads due to maximum lift
forces.

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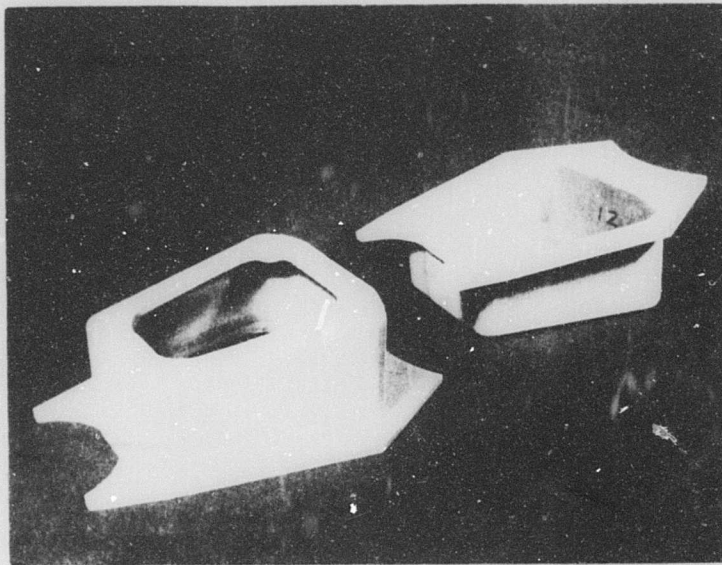
Figure 7.   Shear Box.
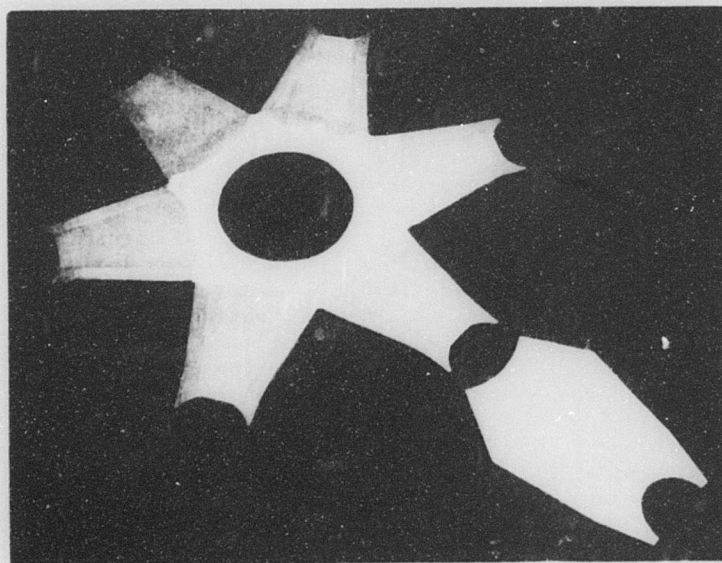
Figure 8.   Cover Plates.

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Bushings

The torque and the lift forces are transmitted through a central hub unit (page 225). Due to requirements for interchangeability with the present titanium hub, this part is designed such that it is identical with respect to principal attachments and fit to the main shaft. It is intended to be machined from titanium; however, for the prototype hubs, steel has been used for the purpose of cost reduction. The bonded composite subassembly of the rotor hub is connected with the central hub unit by means of 18 tension bolts which transfer the lift forces from the blades to a flange of the hub bushing. The lift loads are introduced into the bolts over an aluminum ring (4678, p. 219). In this manner the laminated metallic center of the composite hub structure is compressed between a metallic ring and a metallic flange of the shaft bushing. The torque is transmitted by six square keys which grip into matching slots machined in the aluminum sheets of the loop package and in the hub bushing. The components of the central shaft bushing are shown in Figure 9.

The rotor blade hinge pin is supported in the composite hub by a lug insert (4672, p. 219). The inside and the flange dimensions of this bushing are identical to the equivalent dimensions of the present titanium lug and accept the same roller bearings and other elements of the bearing assembly as utilized in the titanium hub. The insert bushing is made of steel and is bonded into the lug of the composite hub arm. To compensate for level variations, aluminum spacers (4680, p. 219) are inserted between the bushing flange and the lower loops. An aluminum lug ring (4679, p. 219) is bonded to the surface of the upper loop and to the lug insert. The position of these bushings in the upper hub assembly is critical with respect to the lower hub plate (Sikorsky Drawing No. 65103-11009-103). The elements of the lug insert assembly are presented in Figure 10.

Composite Hub Assembly

The above-described nonmetallic and metallic components are adhesively bonded together to form the rotor hub subassembly in the shape of a six-pointed star as shown in Figure 11. This subassembly is bolted to the central hub bushing to form the rotor hub assembly specified by WRD Drawing 4670, sheets 1, 2, and 3 (see Figure 56), making it equivalent to the Sikorsky upper hub, Drawing 65103-11010-043 (see Figure 2). The assembled composite hub is shown in Figure 12.

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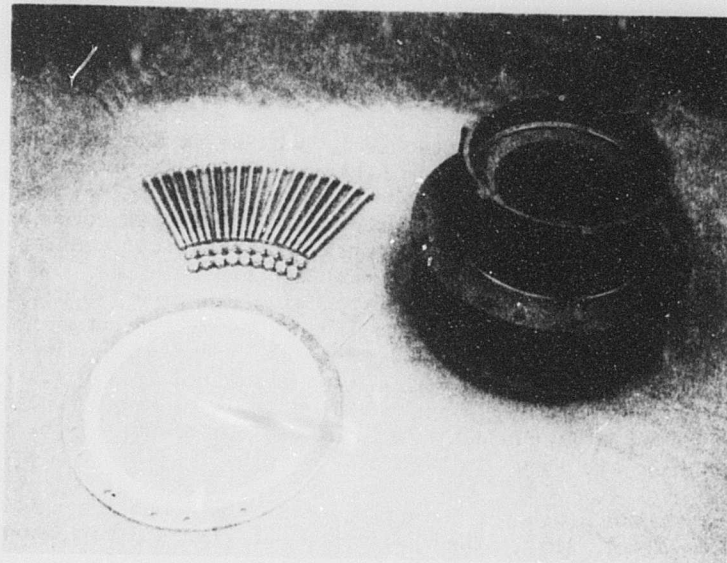
Figure 9.   Shaft Bushing.
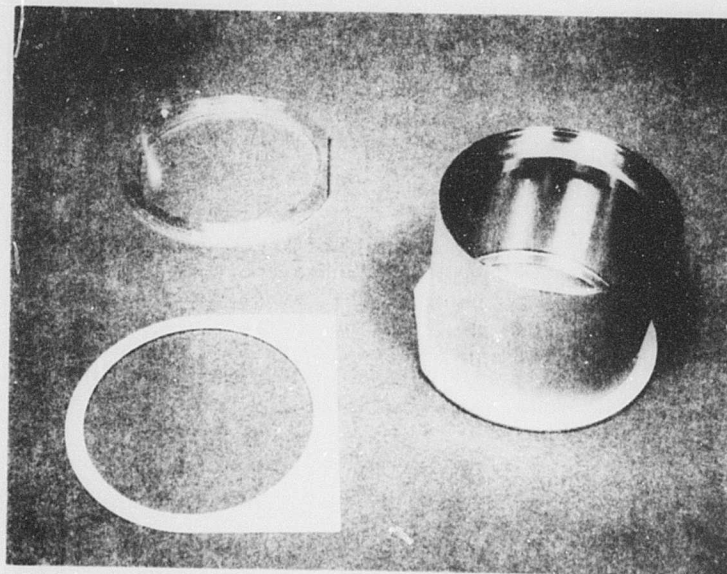
Figure 10.   Hinge Bushing.
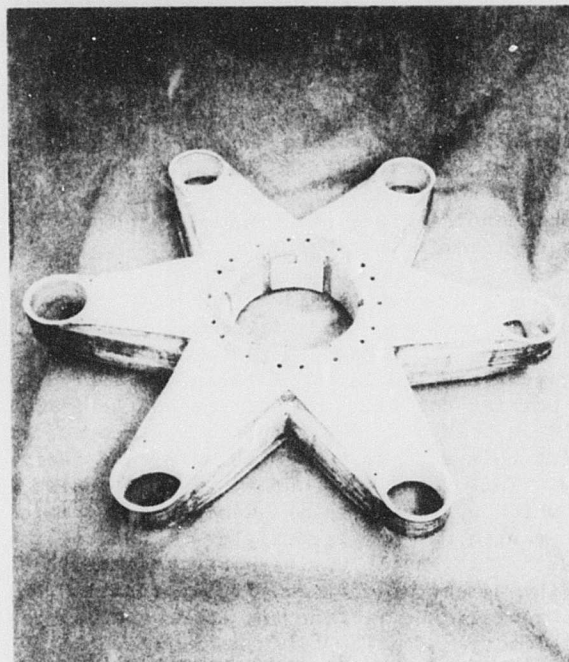
Figure 11. Bonded Hub Subassembly
(Machined).

Figure 12. Assembled Composite Hub.

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DESIGN ANALYSIS

Design Loads

The composite material helicopter rotor hub is designed for both static and fatigue loading conditions. Static loading conditions were obtained from Sikorsky Aircraft Report No. SER-64514, "Main Rotor Head Loads".[1] The fatigue loading condition was established through consultation with Sikorsky Aircraft engineering personnel.

The load designations are shown in Figure 13, with the load application point at the rotor blade hinge. The distribution of the horizontal loads to the upper hub arm and the lower hub plate depends on the position of the roller bearings in the lug insert (D/N 4672). Earlier design analysis was based on the bearing position, as applies to the Sikorsky hub drawing no. 65103-11301-101. This position resulted in eccentricity of the centrifugal force with reference to the location of the neutral axis of the composite hub arm. This version of the hub included also a hoisting hole through the arm, which presented severe design difficulties since its position interfered with the continuous glass fibers of the tension loops. In coordination with Sikorsky, it was possible to improve the design by reducing the bending moment of the centrifugal forces. The design of the composite hub was revised, permitting the upper conical roller bearing to take the vertical load, as applies to an alternate Sikorsky hub drawing no. 65103-11001-102. Also, the requirement for the hoisting hole was dropped, which greatly simplified the composite design. As a result of these modifications, the composite hub design is now similar to the metallic hub assembly as identified by Sikorsky drawing no. 65103-11000-087.

Static Loads

Two load conditions were selected from the Sikorsky Aircraft Report No. SER-64514, page 13: [1]

    Condition TW7F1 - Symmetrical Dive and Pullout (power on)

    Condition TW7F2 - Symmetrical Dive and Pullout (autorotation)

The limit loads for these conditions are summarized in Table I. When establishing the total radial load on the hub arms, the centrifugal force T_c was increased by the reaction load of the moment M_c. This moment is counterbalanced by a damper which is located at a distance of 9.412 inches parallel to the rotor arm center line. The static design ultimate loads for the composite hub were calculated considering the location of the upper roller bearing and the usual ultimate design factor of 1.5. These design static loads are listed in Table II.

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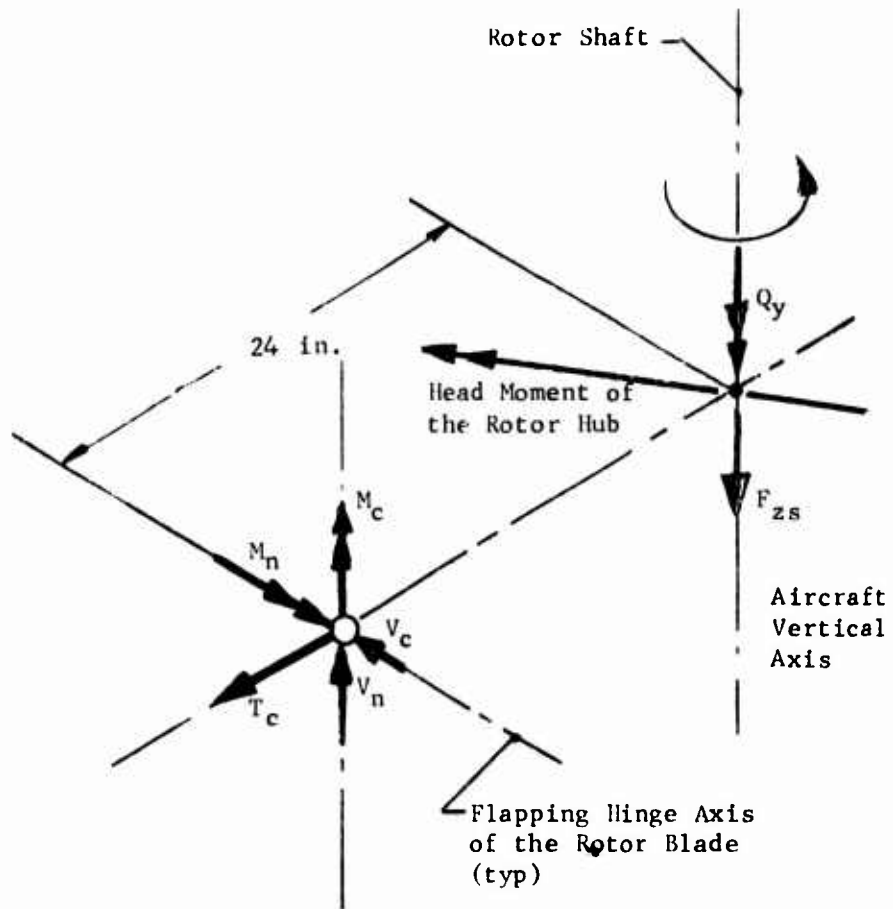
Figure 13. Design Loads.

TABLE I. MAIN ROTOR HEAD LIMIT LOADS		
Flight Condition	TW7F1	TW7F2
FWD Speed, mph	161	161
Main Rotor, rpm	204	215
Main Rotor, hp	7350	-
Rotor Torque Qy, in.-lb	2,271,490	-
Head Moment, in.-lb	1,313,500	1,500,873
T_c, lb	99,000	110,000
V_c, lb	15,775	-
V_n max., lb	34,300	36,560
M_c, in.-lb	74,400	72,000
M_n, in.-lb	-	-
T_c (M_c), in.	7,905	7,650
T_c total, in.	106,905	117,650

TABLE II. STATIC DESIGN ULTIMATE LOADS FOR COMPOSITE HUB		
Flight Condition	TW7F1	TW7F2
T_c, lb (radial)	75,116	82,665
V_c, lb (tangential)	7,389	-
V_n, lb (vertical)	51,450	54,840

Fatigue Loads

Two fatigue load conditions were considered: one based on a steady-state cruise condition, the other on the ground-air-ground condition.

For the steady-state cruise condition, the basic centrifugal force is 83,000 lb limit at 185 rpm. Each blade flaps from -4° to +12° during each rotor revolution. The mean lag angle is 10°. The steady-state in-plane moment is

$$Mc_{steady} = 36,000 \text{ in.-lb limit}$$

Coriolis accelerations due to blade flapping produce a cyclic 2° lag angle, which in turn produces an in-plane cyclic moment.

$$Mc_{cyclic} = \pm 36,000 \text{ in.-lb limit}$$

Therefore, the total moment is

$$Mc_{total} = 36,000 \pm 36,000 \text{ in.-lb limit}$$

The cyclic loads are assumed to act in phase and to produce one cycle for each rotor revolution. The fatigue design of the hub structure was analyzed for 1×10^6 cycles. This cruise condition is also called a low stress/high cycle fatigue loading condition.

For the ground-air-ground condition, the loads were based on the TW7F2 condition (see Table I). These loads are acting on the hub every time the helicopter lifts from the ground for an estimated total of 1×10^4 cycles. This ground-air-ground condition is also called high stress/low cycle fatigue loading condition.

The blade hinge loads generated by these two fatigue conditions were related to the upper hub lug under consideration of the location of the roller bearing and the damper. For these fatigue load conditions, the design loads are equal to the limit loads. Their numerical values are summarized in Table III.

TABLE III. FATIGUE DESIGN LOADS FOR COMPOSITE HUB		
Flight Condition	Cruise	GAG
T_c, lb (radial)	43,300	27,560 ⁺ 27,560
V_n, lb (vertical)	5,740 ⁺ 11,520	18,280 ⁺ 18,280
Number of Cycles	1,000,000	10,000

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Static Stress Analysis

For verification of the structural integrity of the composite rotor hub, two cross sections of the hub arm were analyzed for shear, bending, and axial loads. One section (A-A) is located at 10.9 inches; the other (B-B), at 19.9 inches from the center of the hub. The tension loops which take the radial forces were analyzed for tangential and radial stresses by the methods developed in USAAVLABS Technical Report 69-25. [2] The allowable design stresses were determined as follows:

- Woven Glass Fiber Laminates - The allowable design stresses for Type 1581 and 1543 E-glass/epoxy laminates were obtained from MIL-HDBK-17. [3] These allowable stresses were multiplied by a factor of 0.9 to account for possible strength reduction at elevated temperatures of 160°F.

- Unidirectional Glass Fiber Laminates - Allowable stresses at 160°F for filament wound S-glass roving and Type 1009-26 S-glass unidirectional laminates were taken from strength data published by the supplier. [4]

- Material properties of the sheet molding compound "Structoform S-6300", which is used for the nonstructural spacers, were taken from the supplier's specification sheets. [5]

- Adhesive bond allowable shear stress was based on WRD test data.

- Design allowables of metallic materials were based on MIL-HDBK-5 [6] data.

- Allowables for bearing loads were taken from Timken Engineering Journal. [7]

The properties of composite sections consisting of laminates made from different types of fiber material, such as combinations of unidirectional tape with woven fabric, were determined analytically, utilizing the established procedures of composite material structural mechanics. The properties of composite hub sections such as A-A or B-B were also determined by considering the different stiffness moduli of the section elements as well as the interaction of normal and shear stresses. It can be said generally that the fibrous composite material is shear critical due to limited shear allowables of the organic resin. This deficiency was overcome by fiber orientations such as ± 45° and combinations of this orientation with 0° orientation. However, the structure remains shear critical even after positive margins of safety have been achieved for all investigated locations and load conditions. The margins of safety as calculated by

$$ MS = \frac{Ultimate\ Stress}{Applied\ Stress} - 1 $$

are summarized in Table IV. It shows that the smallest margins of safety are for shear in the upper plate (due to drag loads) and the highest for tension in the loops (due to centrifugal forces).

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		TABLE IV.	MINIMUM MARGINS OF SAFETY		
Location	Item	Load Condition	Type of Stress	M.S.	Appendix I Sheet No.
Section A-A	Lower Plate	TW 7F2	Tensile	+0.46	120
Section A-A	Upper Plate	TW 7F2	Compression Buckling	+0.87	121
Section A-A	Web @ N.A.	TW 7F2	Shear	+0.18	17
Section A-A	Upper Plate	TW 7F2	Shear	+0.21	122
Section A-A	Lower Plate	TW 7F2	Shear	+0.11	24
Section A-A	Upper Plate	TW 7F1	Shear	+0.024	39
Section B-B	Lower Plate	TW 7F2	Tensile	+1.16	126
Section B-B	Upper Plate	TW 7F2	Compression Buckling	+0.10	51
Section B-B	Web @ N.A.	TW 7F2	Shear	+0.68	128
Section B-B	Upper Plate	TW 7F2	Shear	+0.09	59
Lug	Upper Strap	TW 7F2	Combined Tangential and Radial	+0.65	65

The stress analysis of the composite hub structure is presented in Appendix I. It includes evaluations of the earlier design of the hub and its components and of the subsequent design revisions that led to the configuration as built and tested. The M.S. values and respective Appendix I sheet numbers listed in Table IV refer to the latest design.

Fatigue Stress Analysis

It is always more difficult to get reliable fatigue allowables than static allowables, and the theoretical prediction is less reliable. This is primarily due to the fact that the fatigue failure mechanism of composite materials is more complex and presently less understood than the failure criteria at ultimate static loads. The prediction is further complicated if laminates with combinations of different fibers (straight and woven) and different orientations (0° and 45° to the load direction) have to be analyzed.

Whittaker's approach to the analysis of the fatigue performance of the composite rotor hub was the development of workable diagrams based on reported reliable fatigue data on the basic fiber materials. Since the principal structural laminates are constructed from unidirectional tapes and woven fabrics, working diagrams for these materials were developed analytically. They were based on constant life fatigue diagrams for selected conditions, as published in the following reports:

- AFML Technical Report No. TR-64-403 [8]

  Unidirectional S-glass/epoxy laminates loaded parallel to the fiber.

- Forest Products Laboratory Report No. 1823-B, Figure 43. [9]

  Unidirectional S-glass/epoxy laminates loaded perpendicular to the fiber.

- WADC Technical Report No. TR-55-389 [10]

  Woven 1581 E-glass/epoxy laminates loaded parallel to the warp fiber. The equivalent diagram for shear loads at 45° to the warp was estimated from the same data.

- USAAVLABS Technical Report 69-9 [11]

  Woven 1543 E-glass/epoxy crossply laminate loaded in shear at + 45° to warp direction.

Working Goodman diagrams were produced from the constant life fatigue diagrams. Using appropriate stress ratios (R), S/N diagrams were then constructed and time to failure initiation was calculated. These diagrams are shown in Appendix I.

The results of the fatigue analysis show that the failure initiation times for tension loops are much greater than for shear panels; however, slight increases in the allowable stress levels would result in very large increases in failure initiation times.

Weight Analysis

The estimated and the measured weights of all components which go into the helicopter hub assembly and also the total weight of the composite hub are summarized in Table V. Generally, the discrepancies between the estimated and the actually measured weights are minor. The total estimated weight of a hub with a titanium center is 419 lb; the actual weight of hub no. 1 with a steel center is 512 lb, which would be reduced by 100 lb to 412 lb with a titanium center. In comparison with the present titanium roduction hub, this weight is disappointingly high. Therefore, an analysis was performed of a possible weight reduction and of the influence which certain component groups have on the total weight.

The composite hub design was, of course, prepared considering minimum weight requirements, but for reasons of cost savings the weight was not fully minimized. Therefore, further weight reduction is possible, not only by using titanium for the hub center (already reflected in the above weight figures) but also by a more weight-conscious design. We believe that it is possible to reduce the weight of the hub center, of the filament loops, of some spacers, and of the shear boxes. This weight reduction would be in the order of 59 lb. Reduction of the outer diameter of the metallic center hub would reduce the width of the loops and could result in a weight savings of 35 lb. A composite hub thus optimized would weigh 412 - 59 - 35 = 318 lb.

The use of orthotropic materials in the design of the six-pointed star makes a number of components unavoidable which do not directly contribute to the structural performance of the assembly. Such components are bearing inserts, various spacers, fasteners, and adhesive materials, which amount to approximately 82 lb "nonstructural" weight of the prototype hubs. Without those items, the pure structural weight of the composite hub would be approximately 236 lb.

The principal structural deficiency of fibrous composite materials is their relatively low shear strength and shear stiffness. This requires incorporation of laminates with ± 45° fiber orientation to the load direction, which improves the shear properties considerably but does not contribute much for other load directions. The composite hub includes such additional elements in the form of shear boxes and shear plates, which amount now to 55 lb and would be approximately 51 lb for the optimized design.

As a result of this analysis, the fact should be accepted that the tension loops are very weight effective, but due to other material deficiencies the present design of the composite hub, even if optimized, will still weigh approximately 318 lb, or 38% more than the solid-titanium hub

TABLE V. WEIGHT SUMMARY

Item No.	Dwg. No.	Name	Unit Weight (lb) Estimated	Unit Weight (lb) Measured	Number Required	Total Weight (lb) Estimated	Total Weight (lb) Measured
1	4671	Hub, Steel	249.25	227.75	1	249.25	227.75
2	4672	Insert, Lug	4.91	4.89	6	29.46	29.34
3	4673	Laminate, Loop	2.18	3.33*	36	78.48	119.76*
4	4674	Plate, Lower	8.02	9.99	1	8.02	9.99
5	4675	Spacer, Mold	0.57	0.56*	66	37.62	36.81*
6	4676	Spacer (Al)	0.12	0.12	12	1.43	1.43
7	4677	Spacer (Al)	3.75	3.56	6	22.50	21.36
8	4678	Ring, Hub	3.67	3.67	1	3.67	3.67
9	4679	Ring, Lug	0.31	0.30	6	1.86	1.80
10	4680	Spacer, Lug	0.19	0.22	6	1.14	1.34
11	4707	Spacer (GRP)	0.06	0.06	16	0.96	0.96
12	4670-1	Cover	2.71	2.84	6	16.26	17.04
13	4670-4	Basket	9.03	9.69	6	54.18	58.13
14	4670-7	Tape	0.04	0.04	12	0.48	0.48

*Weight prior to final machining.

TABLE V. Continued

Item No.	Dwg. No.	Name	Unit Weight (1b)		Number Required	Total Weight (1b)	
			Estimated	Measured		Estimated	Measured
15	4670-8	Tape	0.04	0.05	12	0.48	0.60
16	4670-10	Tape	0.05	0.06	120	6.00	7.20
17	-	Adhesive	-	-	-	1.33	-
18	MS20009-116	Bolt	0.64	0.64	18	11.47	11.47
19	MS20365-918C	Nut	0.08	0.08	18	1.37	1.39
20	MS20365-524	Nut	-	-	12	-	-
21	AN5-51A	Bolt	0.13	0.13	12	1.59	1.59
22	AN960-516	Washer	-	-	12	-	-

Weight of bonded and machined subassembly (S/N 1)
including items 3 to 7, 10 to 13, 14 to 17 — Estimated 228.88 / Measured 226.29

Weight of metallic components (S/N 1)
including items 1, 2, 8, 9, 19 to 22 — Estimated 298.67 / Measured 277.01

Total weight of assembled hubs:

with steel center — 527.55

with titanium center — 419.20

Hub No. 1 with steel center — 511.44

Hub No. 2 with steel center — 504.59

supplied to WRD. It appears,therefore,that a justification for utilization of nonmetallic composite materials as direct replacement for a titanium helicopter hub of the selected configuration should be sought not on the basis of weight only but on other parameters, such as ballistic survivability, low crack propagation, or production cost.

On the other hand, the fibrous composites could be much more weight efficiently utilized if the hub could be designed strictly for best use of composite material potential, so that the vertical load would also be resisted by members made from essentially unidirectional material. This would mean not just a functional replacement of an existing metal hub, but a new original design of the rotor hub system with composite materials. This optimized composite design concept would lend itself particularly to very large rotor hubs, for which a titanium forging would be impractical and much too expensive.

CONSTRUCTION OF COMPOSITE HUB

Fabrication of Hub Elements

In the following paragraphs the fabrication of those composite hub elements which are of major importance for the structure and which involve specialized fabrication methods will be described. The metallic parts of the assembly are considered conventional, and a description of their machining is not warranted. However, fabrication of the following hub elements will be discussed in some detail:

Filament-Wound Loops

Molded Spacers

Laminated Shear Boxes

Laminated Shear Tapes

Laminated Cover Plates

In addition, the adhesive bonding operations of the hub subassembly and the final hub assembly shall be reported.

To facilitate definition of the parts in the discussion, the 4600 serial numbers are added which refer to Whittaker drawing numbers of the respective parts. Copies of the actual drawings are presented in Appendix II.

Filament-Wound Loops (D/N 4673)

The tension loops are fabricated by winding a preimpregnated fiber glass roving over a flat shape which has the geometry of the internal loop outline. This shape is controlled by the aluminum inserts 4673-1 and 4673-2. The tension loops were wound with 20-end S-glass roving preimpregnated with a 21.8 $^{w}/o$ content epoxy resin. Winding was performed in a special tool (D/N 4687) which controls the thickness of

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the filament-wound section. It consisted of two heavy platens which
were bolted together after the aluminum inserts were placed inside
the platens over locating centers. This fixture is shown in Figure 14.
A number of the initially wound loops, which were produced in the
winding fixture as delivered by the subcontractor, were not of con-
sistent quality. To achieve more reliable results, several improve-
ments of the winding fixture, as well as of the winding and curing
processes, were made, which resulted in loop assemblies of uniform
and reproducible good quality. Per request of the Project Officer,
each loop contained one continuous 12-end lead glass roving.

Molded Spacers (D/N 4675)

The spacers were molded in a form tool (D/N 4686) from a low-cost
sheet molding compound which consisted of chopped glass fibers and a
polyester resin. This material flows under heat and high pressure and
fills the mold in all details. The sheet was precut to the approxi-
mate shape of the spacer sections by means of steel rule cutting dies.
The mold and the cutting dies are shown in Figure 15.

Laminated Shear Boxes (D/N 4670-4)

The material used for the shear boxes of the prototype hubs was style
1543 epoxy resin impregnated E-glass fabric. The initial design
called for a unidirectional glass fiber tape; however, its high cost
seemed to be unjustifiable for the prototype hubs. The glass fabric
plies were cut at 45° to the warp orientation according to a developed
pattern and laid up in a female mold (D/N 4708), which is shown in
Figure 16. They were placed alternately, changing the warp direction
from plus to minus 45° to the symmetry axis of the shear box. The
material was very drapable in the prepreg form and could be easily
shaped to conform with the mold contours. To achieve high density,
the laminate was precompacted as the thickness was built up. After
autoclave cure, the boxes were machined according to the final flange
contours.

Laminated Shear Tapes (D/N 4670-7, -8, -10)

The shear tapes were prepared from a unidirectional glass fiber tape.
Tape plies were cross-laminated to form a tape with ± 45° fiber
orientation to the longitudinal axis. The contour was then stamped
out by means of steel rule cutting dies, as shown in Figure 17. The
shape of the shear tapes was bent to match the tension loop and shear
box contours during the actual hub assembly operations.

Laminated Cover Plates (D/N 4670-1 and 4674)

The top and bottom cover plates consisted of style 1581 epoxy resin
impregnated E-glass fabric and unidirectional epoxy resin impregnated
S-glass tape. The tapes were used essentially for transmitting axial

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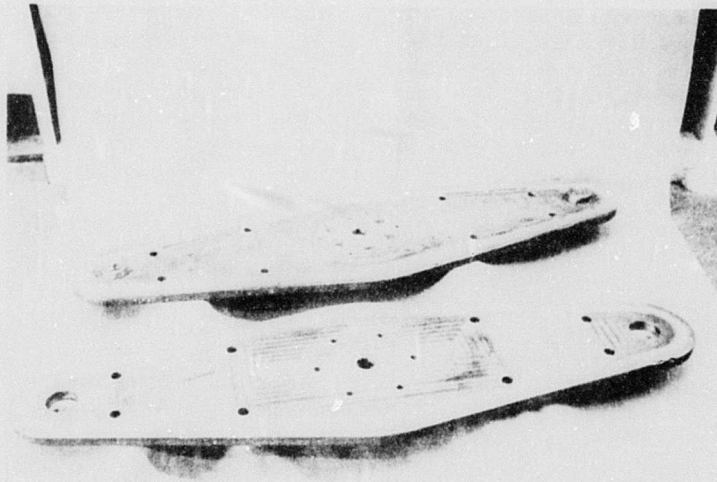
Figure 14.   Winding Fixture.

Figure 15.   Spacer Mold and Cutting Dies.

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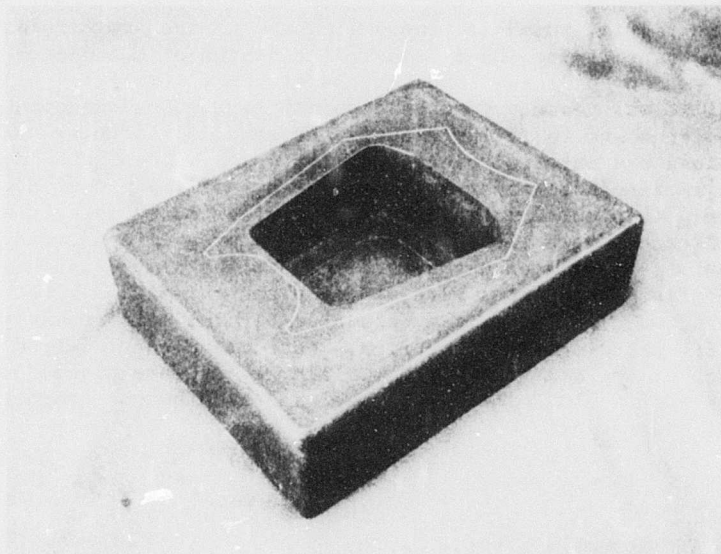
Figure 16. Mold for Shear Boxes.
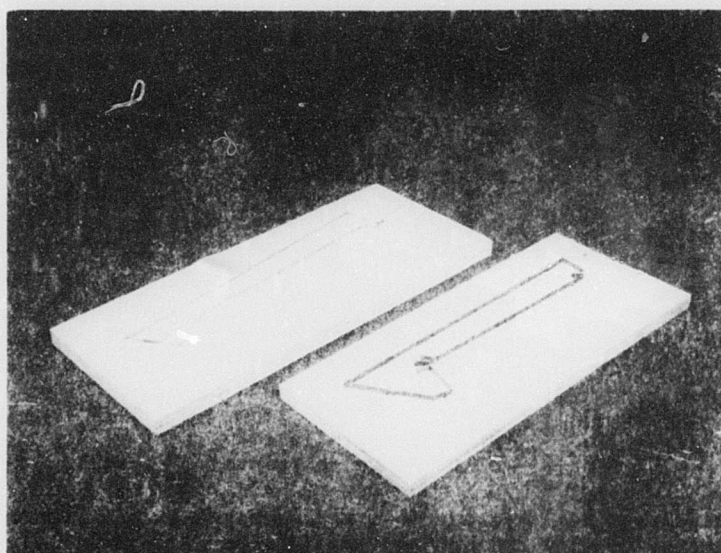
Figure 17. Shear Tape Cutting Dies.

loads. The fabric, which is placed at ± 45° to the symmetry axis, served for transmitting shear loads. The design of the plates prescribes a variety of shapes and lengths of the interspersed plies. Therefore, it was necessary to develop the laminating sequence with paper templates and to follow exactly the required layup by numbering the templates and material pieces. After completion of the layup, the plies were held together and in place by application of a vacuum bag and were then cured in an autoclave. After cure, pockets with smaller thickness were filled with 1581 type prepreg and cured, and the contour of the plates was ground. The cover plates (4670-1) were laid up on flat tool plates with taped-on contour strips. The lower plate (4674) was laid up on the base plate of the main assembly fixture with taped-on contour strips. To achieve the required inclination of the arm sections, metallic wedges were placed on the base plate (D/N 4706). The lower panel is shown on the laminating fixture in Figure 18.

Hub Assembly

Bonded Hub Subassembly (Ref: D/N 4670)

The bonded subassembly of the composite hub is the principal assembly of all components made mainly from fibrous nonmetallic materials. The assembly is achieved by adhesive bonding of the following elements of the hub structure, which are listed in appropriate sequence of their incorporation into the assembly.

		Part Name	Drawing No.
Step 1:	6	Shear Boxes (GRP)	(4670-4)
	16	Spacers (GRP)	(4707)
	36	Loops (GRP)	(4673)
	66	Spacers (GRP)	(4675)
	144	Shear Tapes (GRP)	(4670-7, -8, -10)
	12	Spacers (aluminum)	(4676)
Step 2:	6	Spacers (aluminum)	(4680)
	6	Spacers (aluminum)	(4677)
	1	Lower Plate (GRP)	(4674)
Step 3:	6	Covers (GRP)	(4670-1)
	6	Lug Inserts (steel)	(4672)
	6	Lug Rings (aluminum)	(4679)

The adhesive used for this assembly was prepared so that it would prevent excessive flow and achieve gap filling properties. It consisted of Shell Epon 828/NMA/BDMA resin system with an addition of 12 1/2% Cabosil.

Figure 28. Lower Plate Laminating Fixture.

The assembly was performed on the assembly fixture (D/N 4706); however, the wedges used for molding the lower cover were removed. The upper edge of the hub assembly was the reference plane, and the hub was assembled in the upside-down position, with the flanges of the shear boxes placed on the fixture base plate first. The location of the loops and molded spacers was controlled by a short cylinder in the center and by six pins located at 60° spacing. These pins were designed to locate the hub arms exactly a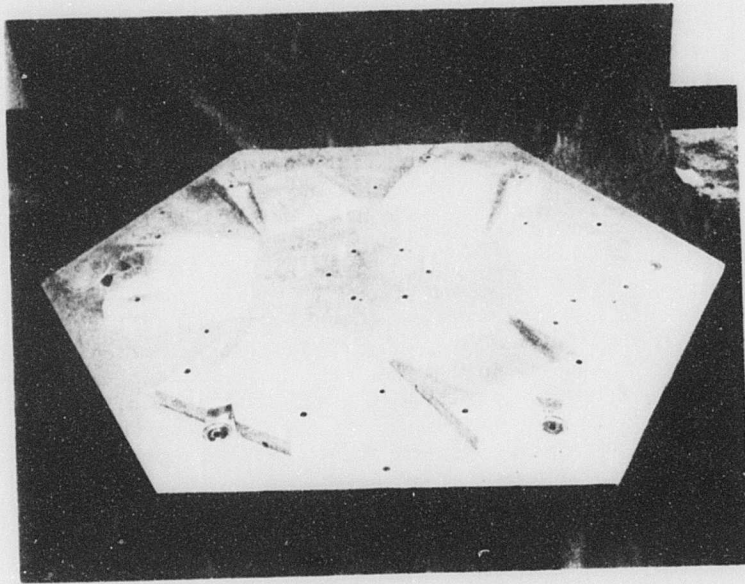ngularly but to provide some movement radially so that any possible change in radius at the elevated curing temperature could be observed. It should be noted that all components were prefit in the fixture and then sand-blasted to provide a reliable bonding surface. They were then installed, keeping the same sequence, and the adhesive was brushed on their surfaces as required.

During the Step 1 assembly operation, loops and spacers were mechanically compacted, and their proper dimensional location from the base plate was continually measured and, if necessary, corrected. Figure 19 shows the bonded subassembly after completion of Step 1. A vacuum bag was then applied and the whole part cured in the autoclave, as shown in Figure 20. After completion of the cure, excessive resin was chipped off and the loop package surface slightly ground to remove excessively protruding shear tape edges.

In Step 2 bonding, the thick aluminum spacers and the lug face spacers were fitted and the lower plate was bonded. This was also done in the autoclave. After this step, the hub subassembly was ready for machining.

The center hub diameter was bored and the lower hub center was spot faced on a horizontal lathe. The holes for the lug inserts and the spot face for the insert flanges were then machined on a radial boring machine. The key grooves in the hub center and the bolt holes were also provided. The hub assembly in this condition is shown in Figure 11.

Step 3 included adhesive bonding of the cover plates and the lug insert bushings, and installing of the lug tie bolts. The location of the bushings is critical for alignment with the lower hub plate (see Figure 2). A close tolerance location of the bearing inserts can be achieved only with a precision bonding fixture or by utilization of hub components which would guarantee an alignment with the lower hub plate. Since neither was available, the prototype inserts (D/N 4672) were located by the lower lug surface and by their centering in the lug bore.

The Step 3 bonds were made with a room-temperature-cured epoxy adhesive.
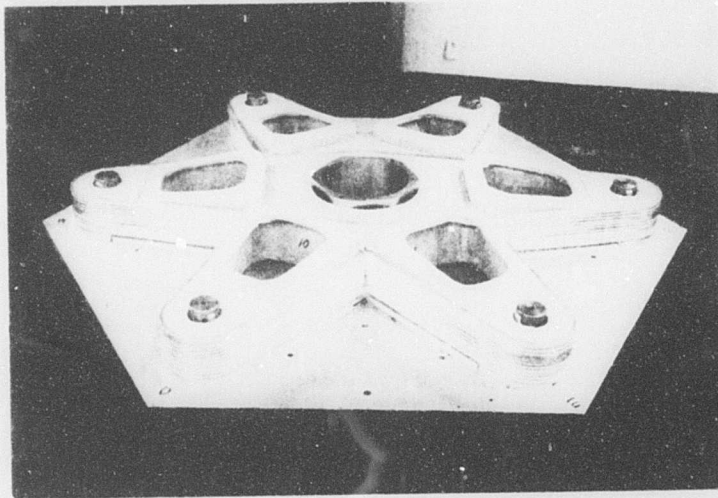
Figure 19.   Bonded Subassembly.
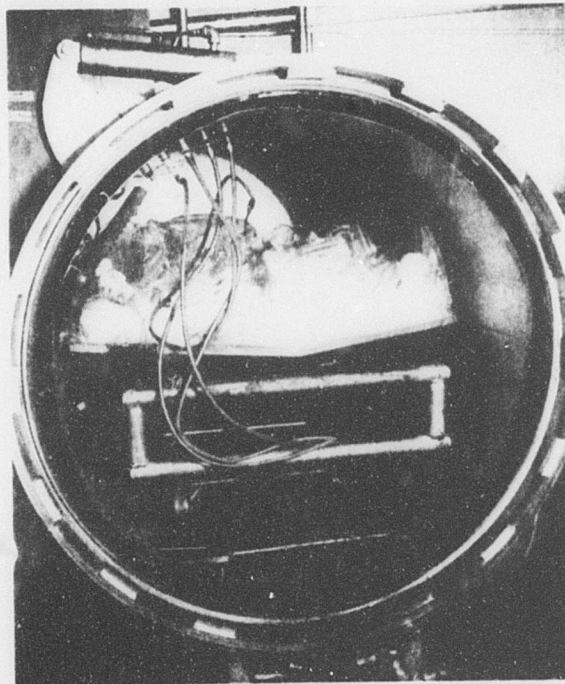
Figure 20.   Autoclave Curing of
the Composite Hub.

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Final Hub Assembly (D/N 4670)

The final hub assembly was accomplished by inserting the metal hub
(D/N 4671) into the keyways of the composite hub subassembly. The
connection was provided by bolts which compressed the composite hub
subassembly between the ring (D/N 4678) and the flange of the metallic
hub center. A uniform torque of 90 ft-lb was applied to these bolts.
The fully assembled composite hub is shown in Figure 12.

Quality Control

All materials and components were subjected to quality control. All
vendors were required to provide certifications of compliance including
data and drawings. The manufacturing process for the components and the
assembly operations were checked for concurrence with job travelers and
design drawings. The following are the QC tests conducted on preimpreg-
nated fiber glass materials:

- 20-End Glass Roving

	Solids	Volatiles	Flow
Specification, %	19 ± 3	3 max	
Vendor average lot test, %	21.80	2.05	
WRD average roll test, %	21.00	2.20	10.80

Of the rolls tested, one was rejected due to insufficient
flow. Gel time tests at 200°F were conducted on all rolls
to determine the best curing temperature cycle.

- Glass Fabric Prepreg Types 1543 and 1581

	Solids	Volatiles	Flow
Specification, %	41 ± 3	1.5 max	12 - 27
Tested, average, %	41.5	0.18	19

For process optimization, the gel time of 1581 material was
determined for 150°F, 200°F, and 250°F and resulted in 150,
65, and 6 minutes, respectively. For 1543 prepreg, the gel
time at 200°F was shorter and measured between 11 and 16
minutes. The curing cycle was adjusted accordingly. This
prepreg was not used in combination with any other material.
Therefore, the difference in gel time was acceptable.

- Unidirectional Glass Fiber Tape

The specified resin content was 25 ± 3% by weight, and the
gel time was 6 minutes average at 300°F. This was confirmed
by WRD QC tests.

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All manufactured detail parts were inspected for dimensional accuracy, general appearance, uniformity, and presence of any delamination and other anomalies. Special attention was given to the structurally important components such as tension loops, shear boxes, and cover plates. As reported previously, a number of initially produced tension loops were rejected, which resulted in modification of the winding tool and the curing process. Coupons were cut from shear box and cover plate laminates and inspected for density and resin content. The metallic components made by subcontractors were inspected by dimensional check and by vendor material conformance certification.

During the assembly operation, dimensional checks were carried out to control the thickness and uniformity of the laminated loop package. In cases of discrepancy, corrections were made by locally adding thickness compensating plies of 1581 type prepreg. Fortunately, a reduction of thickness was not necessary because the actual adhesive thickness turned out to be somewhat under the adhesive thickness assumed in the design drawing.

Records were kept of all inspection steps performed.

Tooling

For the fabrication of the prototype composite hubs, the following tools and fixtures were utilized:

Tool Name	For Part Number	Tool Number
2 Winding Molds and Accessory	4673	3027-1601
1 Molding Die	4675	-1602
1 Steel Rule Die	4675	-1603
1 Steel Rule Die	4675	-1604
1 Steel Rule Die	4670-8	-1605
1 Steel Rule Die	4670-7	-1606
1 Assembly Fixture and Accessory	4670, 4674	-1607
2 Molds	4670-4	-1608
1 Holding Fixture	4671	-1609A
1 Test Fixture	4670	-1609B
1 Cutter	4671	-1610
2 Steel Rule Dies	4670-10	-1611

EXPERIMENTAL EVALUATION

Material Properties

Loop Tensile Tests (S-Glass with WS 1028 Resin)

The principal design element for the composite hub is the tension loop. Therefore, tests were conducted for determination of loop failure loads. The test specimen configuration is shown in Figure 21. It was wound with the material and cured by a process which was selected for the hub tension loop.

Three specimens were tested to failure at room temperature. The ultimate loads were between 11,000 and 11,500 lb, which resulted in an average stress level of 202,000 psi. To compensate for 160°F temperature, this value has been reduced by 10%, resulting in 180,000 psi ultimate stress used for the stress analysis (see Appendix C).

Molding Compound Shear Tests

Shear tests were conducted on the molding material used for the loop spacers. During the early design period, this material was to be a bulk molding compound, EM 7302 by U.S. Polymeric. The following average room-temperature data were obtained:

Interlaminar Shear

    0.074 to 0.083 inch thick specimens - 4,260 psi

    0.179 to 0.183 inch thick specimens - 2,380 psi

Shear Modulus

    0.076 to 0.084 inch thick specimens - 0.811×10^6 psi

    0.192 to 0.205 inch thick specimens - 1.015×10^6 psi

Based on structural considerations, it was later found that a less stiff material would be more desirable for the molded spacers. Therefore, the EM 7302 compound was replaced by the "Structoform" sheet molding compound by Fiberite Corporation. Tests on the compound no. S-6413 resulted in the following values:

    Interlaminar Shear   -   4,700 psi

    Shear Modulus   - 0.773×10^6 psi

With lower modulus and higher shear strength, this material offered an improvement for this particular application. The final material selected was the Structoform S-6300, which had identical structural properties; however, it required a somewhat lower molding pressure and was available at a lower price than S-6413. It should be noted that

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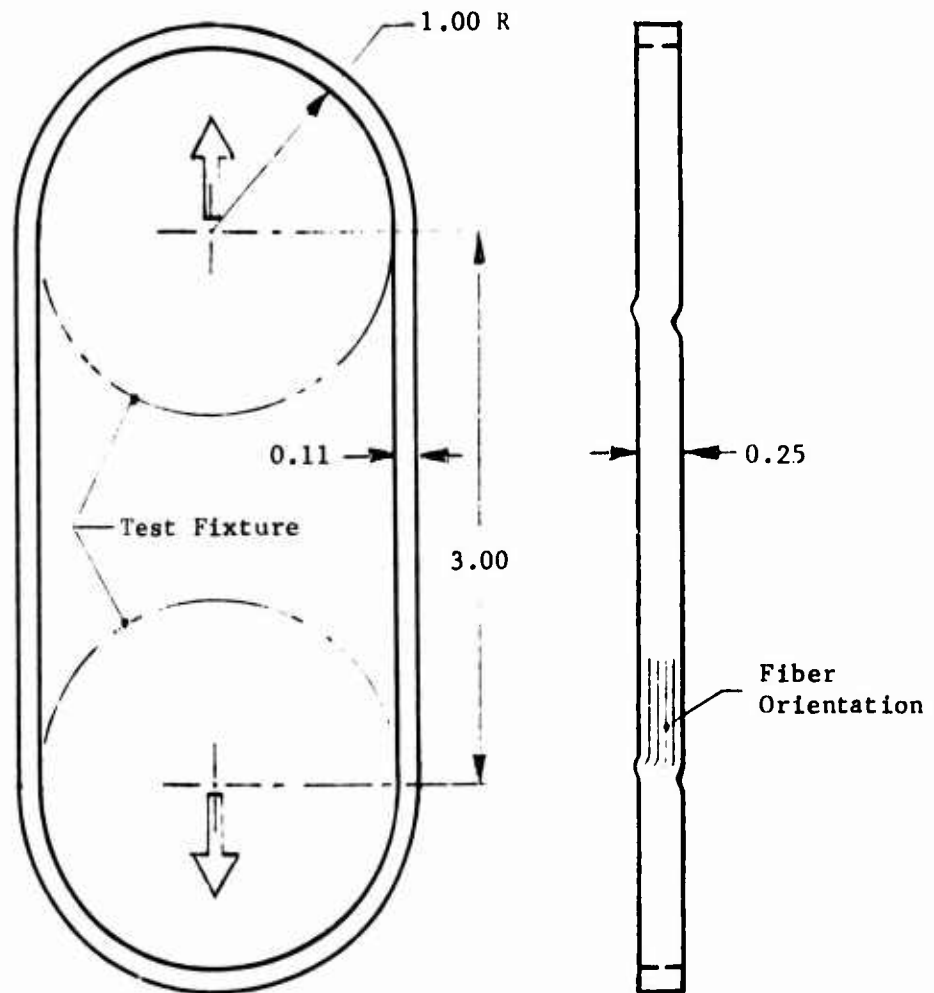
Figure 21. Loop Test Specimen.

data are available on the S-6413 sheet molding compound, which were generated by Whittaker under U.S. Air Force Contract F33615-70-C-1636, "Low Cost, Fiber Glass Reinforced Plastic Fuel Tank," and which included fatigue tests conducted by the Forest Products Laboratory in July 1971. [12]

Adhesive Shear Tests (Hysol EA 934)

The adhesive shear strength was determined by a special specimen representing the shear interface between the upper and lower cover plates, and the shear boxes. It was constructed from aluminum in the form of an I-beam and was tested in bending over a 7.5-inch span (see Figure 22). Of the three tested specimens, the representative bending failure load, P = 8,280 lb, was selected as base for shear stress analysis.

The shear stress at failure was analyzed from the known relationship:

$$f_s = \frac{P \, Q}{2 \, I \, b}$$

where
Q = moment of the beam cap

I = moment of inertia of the I-beam

b = web width

Based on measured I-beam dimensions,

$$f_s = 0.783 \ P$$

$$= 0.783 \cdot 8280$$

$$= 6983 \ psi$$

An ultimate shear stress of 6,500 psi was selected for design analysis.

Process Evaluations

In order to determine the best process parameters, such as temperature, time, pressure, and pot life, a number of fabrication-related material tests were made. These process evaluation tests were conducted to optimize the adhesive bonding, to establish the best curing schedule for co-curing of different types of prepreg materials, and to develop a reliable process for laminating the relatively thick wall of the shear boxes.

- Bonding tests were conducted to evaluate the adhesive for its ability to be applied by brush over a working period of at least three days, which was felt necessary for the duration of the final hub assembly, to determine the compatibility of the adhesive with the P-251S prepreg, and to assure good performance at curing temperatures not exceeding 300°F.

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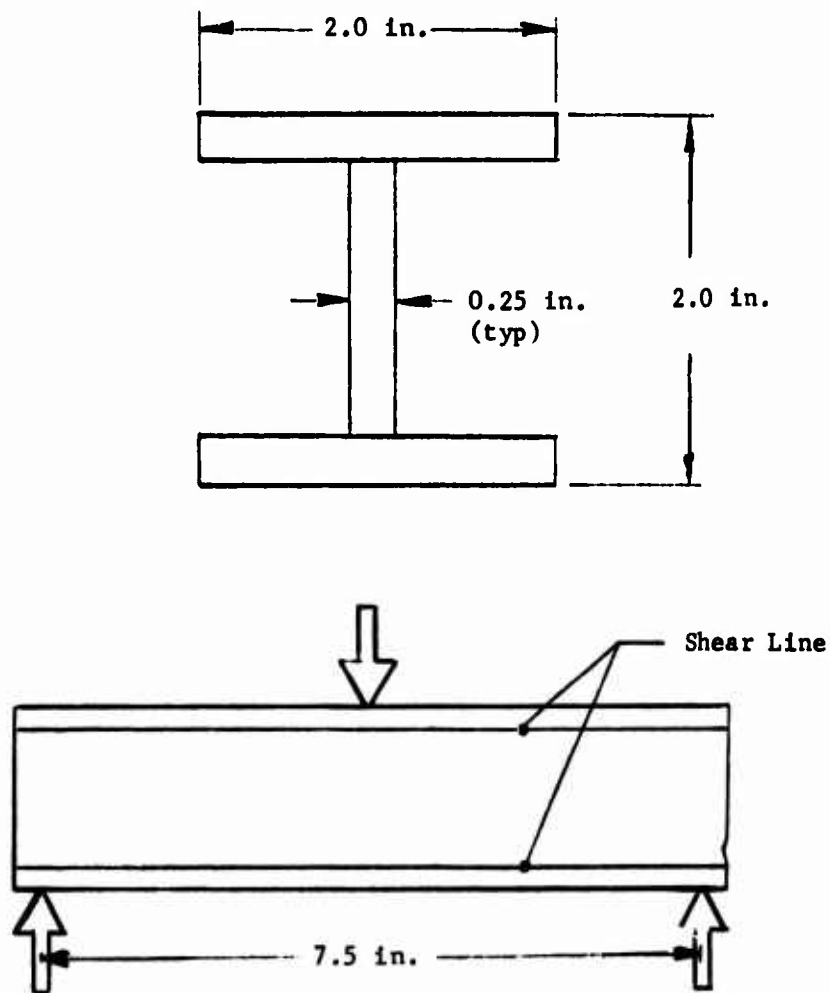
Figure 22. Adhesive Shear Specimen.

Two variations of the Shell Epon 828 adhesive were compared with Hysol EA 934 adhesive with respect to their brush coat life capability:

Adhesive	Temperature	Brush Coat Life
828/NMA/BDMA (100/ 90 / 1)	RT +250°F	6 - 7 days 15 - 20 minutes
828/NMA/BDMA (100/ 90 / 2)	RT +250°F	5 days 15 - 20 minutes
934	RT	120 minutes

The 828 formulation with 2 parts of BDMA per 100 parts of resin was selected. It had a gel time of 25 minutes at 250°F.

Evaluation of adhesion quality of the selected 828 formulation to different materials was conducted with simulated hub material interface conditions, with faying surfaces degreased and lightly sanded. The specimen was a multilayer sandwich representing the tensile loop package. It consisted of eight materials cut to 0.5-inch by 2-inch plates and bonded with the 828 adhesive. Th. sequence of the individual sandwich material layers was as follows:

Aluminum (loop inserts)

Aluminum (loop inserts)

S6300 (spacers), cured

P-251S (shear tapes), uncured

E787 (loops), cured

S6300 (spacers), cured

P-251S (shear tapes), uncured

E787 (loops), cured

This specimen was cured for 2 hours at 300°F and 20 psi pressure. After cure, it was cut in half and the different bond lines were examined by microscope. The inspection resulted in the conclusion that the selected 828 adhesive had good and uniform flow and was void free.

- The design of plates D/N 4670-1 and 4674 calls for lamination of two different prepreg materials: the vacuum bag, 250°F cured Narmco 587/1581 fabric with the 100 psi, 350°F cured 3M P-251S tape. Two specimens were cured in the autoclave at somewhat different cure cycles. The specimens were 4-inch by 4-inch laminates consisting of 9 plies of 1581 fabric and 20 plies of P-251S tape, which were representative for the lower plate laminate (D/N 4674-1).

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The cure cycles and the results were:

	Laminates No.	
	1	2
Preheat temperature, °F	200	200
Minutes to reach 50 psi pressure	65	45
Temperature at 50 psi, °F	275	200
Minutes to reach 90 psi pressure	25	15
Temperature at 90 psi, °F	300	300
Dwell at 350°F, hours	4	4

Both laminates had a good appearance; however, the first was slightly thicker due to less compaction of the upper plies. The second laminate was more uniform and denser and indicated that an earlier application of pressure was beneficial. Therefore, the second process was selected for part lamination.

• The laminate of the shear boxes is relatively thick (approximately 0.5 inch), and the layup is done by hand in a deep female mold. In order to guarantee a high-quality laminate, an evaluation of different layup methods was conducted.

First, a 4-inch by 4-inch, 50-ply laminate was prepared and cured at 50 psi without any compaction prior to curing pressure application. It resulted in a relatively thick laminate with 9.6 mils per ply thickness, a specific gravity of 1.917 g/ccm, and a resin content of 32.9% by weight.

Another laminate sample was prepared in the actual shear box mold using a theoretically developed layup pattern. This laminate had only 5 plies. It was cured in a vacuum bag at 50 psi autoclave pressure. The compaction was good and resulted in 6.7 mils per ply thickness; however, it indicated a need for pattern adjustment.

After this, the first prototype shear box was laminated with a modified pattern. The plies were precompacted, five at one time, at 50 psi, in a vacuum bag with a single outlet. All 50 plies were cured simultaneously. The specific gravity of coupons cut from this box laminate was 1.911 g/ccm. These tests led to the conclusion that the thick box laminate should be compacted and cured in steps. Consequently, the shear boxes were precompacted and stage cured at 50 psi after layup of 15, 35, and 55 laminates. Also, a dual vacuum outlet was used. This resulted in a dense laminate with specific gravity of 2.00 g/ccm.

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Testing of Prototype Hubs

In order to demonstrate basic structural integrity, static and fatigue loads were applied to the hub. Since the hub is made symmetrically with six identical arms, the test program was conducted on only one pair of diametrically opposite arms. As the centrifugal force component of the rotor blade balances itself across these arms, and the lift force at the arm tip bearing is reacted by the center hub, it is necessary to support the rotor hub by the center hub bearing only. The loads that are applied through the arm tip bearing completely stress the hub in a manner similar to that experienced during actual helicopter operation.

The only exception to simulating the testing of the total rotor hub through the use of only one pair of arms is the loading on the center hub spline, for which simultaneous six-point loading of the hub arms would provide a more exact load stress distribution. However, since the center spline of the hub is basically identical to the existing metal hub, no lack of pertinent data was expected to result.

The test plan did not include the chordwise (torque) loading of the rotor hub arms. There were two reasons for not considering this additional load vector. One was that this load does not exist in the most critical condition, which is the symmetrical dive and pullout condition of auto-rotation, reported in the section on design loads (p. 14) as condition TW7F2. Second, no portion of the structure appears to be critical based on the chordwise load vector.

The prototype hubs were tested in a specially constructed fixture (D/N 4747, 4748, 4749, 4750). Radial and vertical loads were applied simultaneously by three hydraulic cylinders. Two were acting on the opposite ends of one tension loop package (double arm); the third was loading one lug of the same arm vertically. The hydraulic power was provided by the pressure system of WRD's high-pressure test facility. A schematic of the test system is shown in Figure 23, and the hub installed in the test fixture is presented in Figure 24. The instrumentation for deflection reading is visible in Figure 25.

In order to acquire as much information as possible on the structural characteristics of the composite hub, both static and fatigue tests were conducted. The original test plan had the following schedule:

Hub No. 1   -   Static loading to failure

Hub No. 2   -   Cycling at high stress level up to 1×10^{4} cycles

             -   Cycling at low stress level up to 1×10^{6} cycles
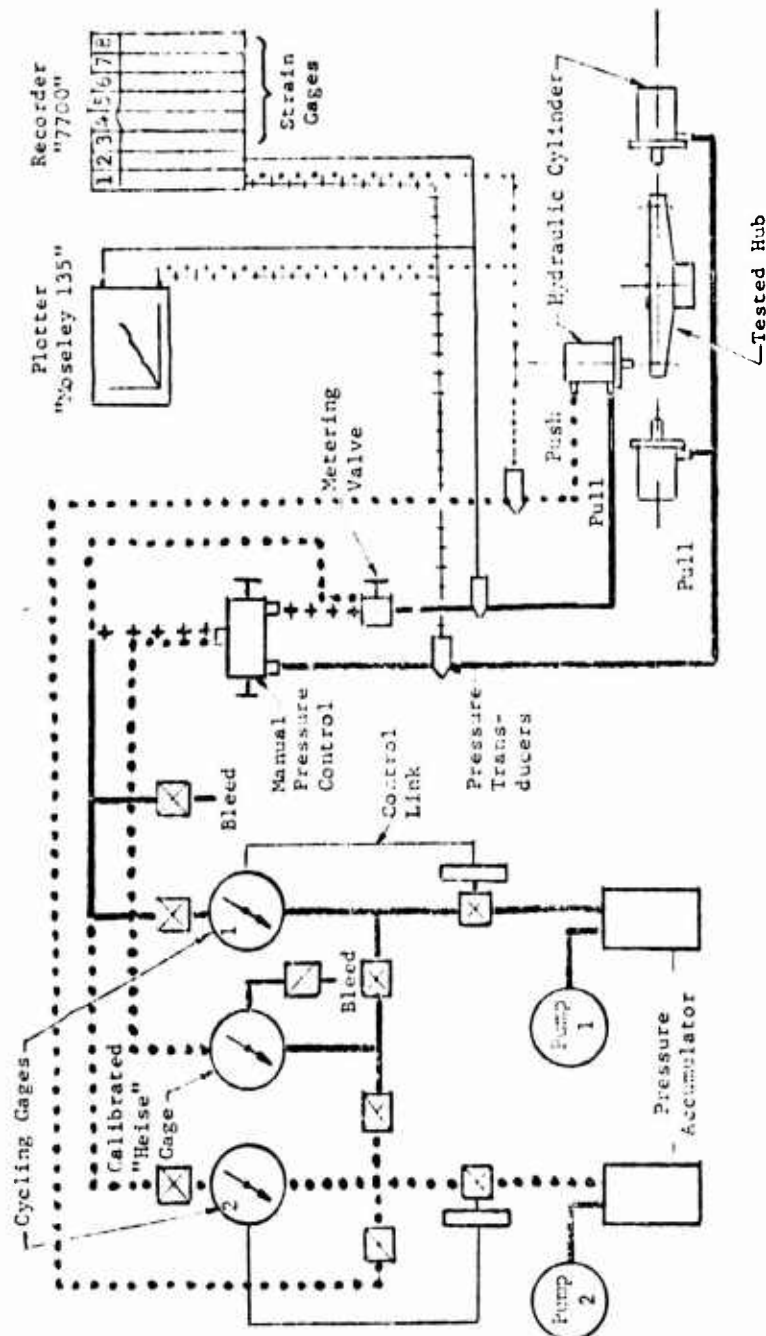
             -   Static loading to failure

Figure 23. Test System, Schematic.

41
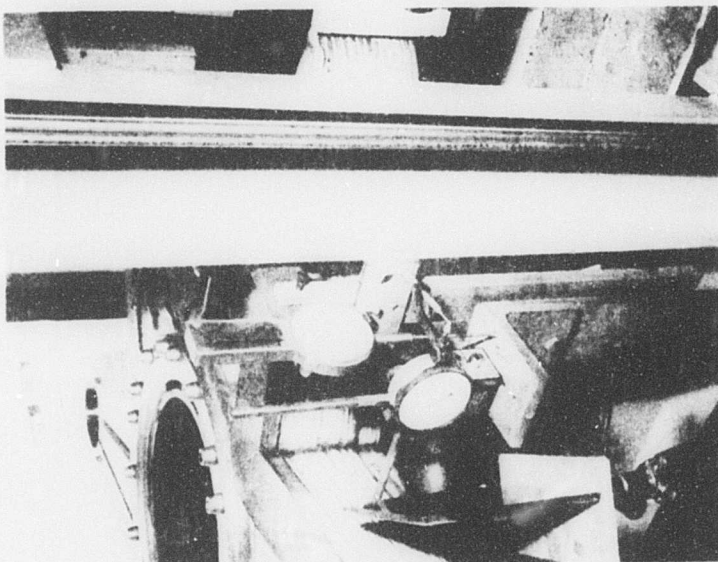
Figure 25. Deflection Reading.
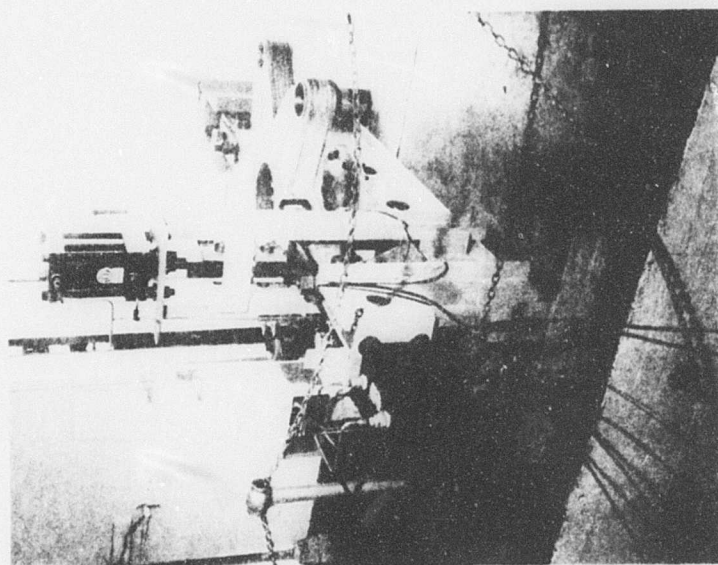
Figure 24. Hub in Test Fixture.

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For reasons described later, this test plan was modified as follows:

Hub No. 1 - Cycling at low stress level

Hub No. 2 - Cycling at high stress level

- Static loading to failure

During the tests,advantage was taken of the multiple test capability of
one hub. This was possible as a result of the selected test method by
which only one pair of hub arms was subjected to test loads. Therefore,
each hub could provide three independent tests, thus increasing the
confidence level without significantly increasing the test expenses.

Static Test on Hub No. 1

The first pair of arms of the prototype hub no. 1 was instrumented
by six strain gages, as shown in Figure 26. The strain gages were
numbered in accordance with the numbers of the Hewlett-Packard
recording channels. Since channels 1 and 2 were recording the pres-
sure in the horizontal and vertical cylinders, respectively, the
remaining channel numbers for the strain gages were 3 through 8.
The intent of these strain gages was to record deformations of the
following hub components:

Gage 3 - Lower panel, tension

Gage 4 - Loop package, shear

Gage 5 - Loop lug, tension

Gage 6 - Upper cover, shear

Gage 7 - Upper cover, compression

Gage 8 - Loop package, tension

The radial and vertical deflections of a selected reference point at
the hub lug were recorded by dial indicators. After checkout of
system functions, the first prototype hub was loaded in accordance
with condition TW 7F2. The ratio of the horizontal and vertical
loads is a constant factor of 1.5073. This proportionality was
marked on the Moseley 135 control panel and maintained by manually
adjusting the pressure loads in the horizontal and vertical cylin-
ders. It was the intent to load the hub to failure or to 3200 psi
line pressure, whichever was less. The 3200 psi limit was dictated
by the safety of the test equipment.

By adhering to the original test plan, the hub was statically loaded
with the expectation that the following design loads would be
reached prior to failure:

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Figure 26. Strain Gage Locations.

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	Horizontal	Vertical
Limit, lb	55,110	36,560
Ultimate, lb	82,665	54,840

With increasing load, the hub produced low cracking noises, which are typical during testing of fibrous composites. The test was inter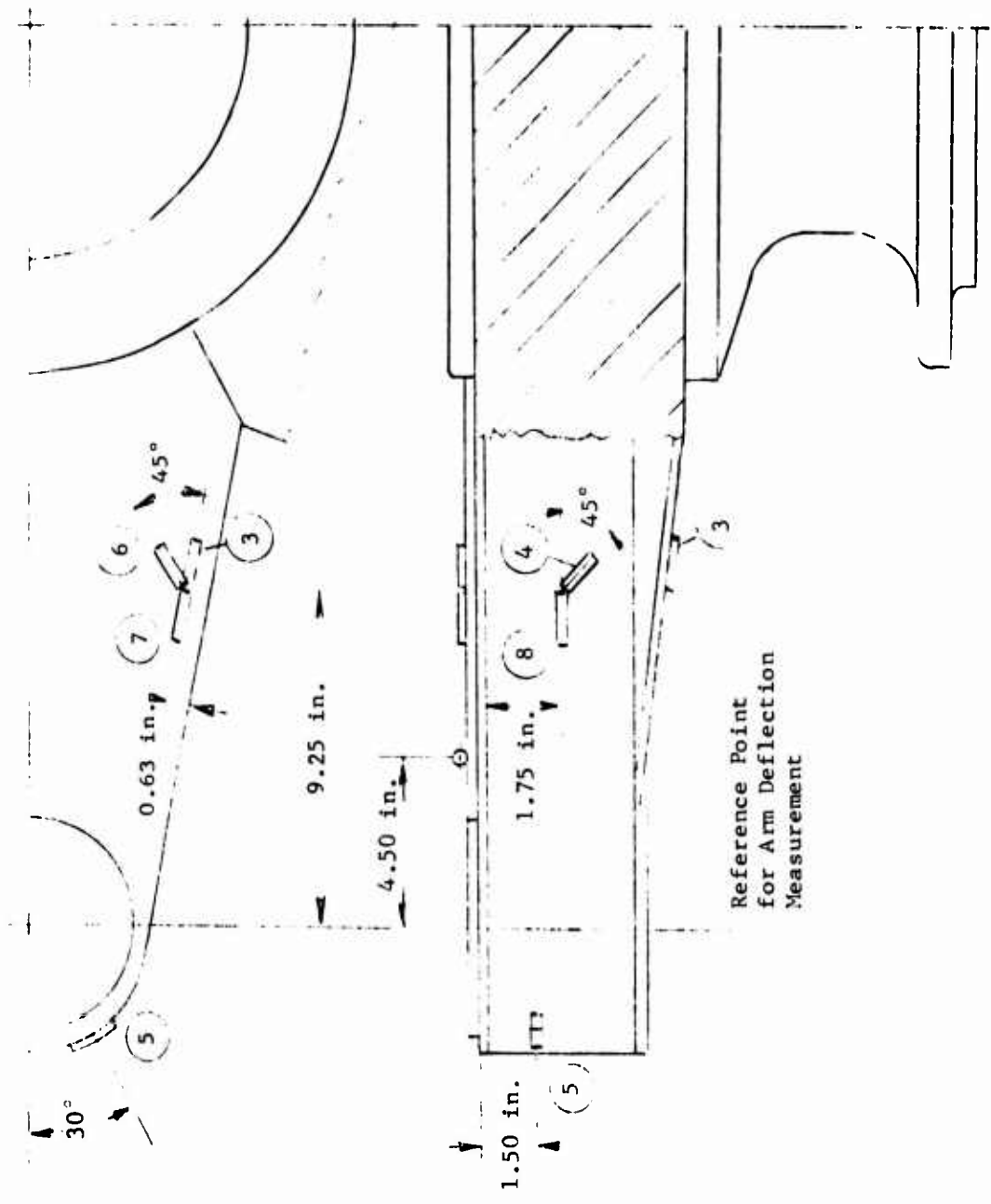rupted when a very loud cracking occurred. At this instant the hub arm supported 38,956 lb horizontally and 25,701 lb vertically. Inspection revealed an adhesive shear failure on the tension side of the hub arm between the lower plate and the shear box surfaces, which was visible by cracks developed on both sides of the test arm.

Analytical comparison of the design stress analysis and strain gage reading showed good correlation of the strain levels, but indicated a bond failure at significantly lower shear stress level than expected based on specimen testing. Inspection of these particular bonded joints on all six arms of the two hubs indicated a possibility of inadequate bond quality, mainly due to poor matching of the adjacent surfaces of the shear boxes and the lower plates. The reasons were finally traced to the design and fabrication approach by which the surface of the lower plate became uneven. As a result, the shear load transfer between plate and box was irregular, the plate overloaded, and the bond was inadequate to resist the shear stresses. This reasoning was supported by the strain gage records shown graphically in Figure 27. The graph shows that the development of strain with increased load was normal and followed a generally linear pattern without any major irregularities that could indicate more basic structural deficiencies. Gage no. 3, which was attached to the lower panel, was very uniform but had the largest strain value.

Of interest also were the deflection measurements by a horizontal and a vertical dial indicator. They are plotted in Figure 28. They indicate that, compared with the tested deflection values of the titanium hub, the radial stiffness of the composite hub was higher. The relative vertical stiffness was higher at low strain levels but lower at higher stress levels, probably due to the earlier outlined shear limitation of composite materials.

Joint Correction

Since the potential structural deficiency of all bonded joints between the lower plate and the boxes would limit the structural evaluation of the prototype hubs, the Project Officer approved rework of the joint by which an improvement of the shear transfer was to be achieved. After reviewing several possibilities for corrective actions and relating them to the remaining funds, it was concluded that the only possible correction could be implemented on hub no. 2, to which the upper cover plates had not yet been bonded and where, therefore, access to the internal flange of the shear box was available.
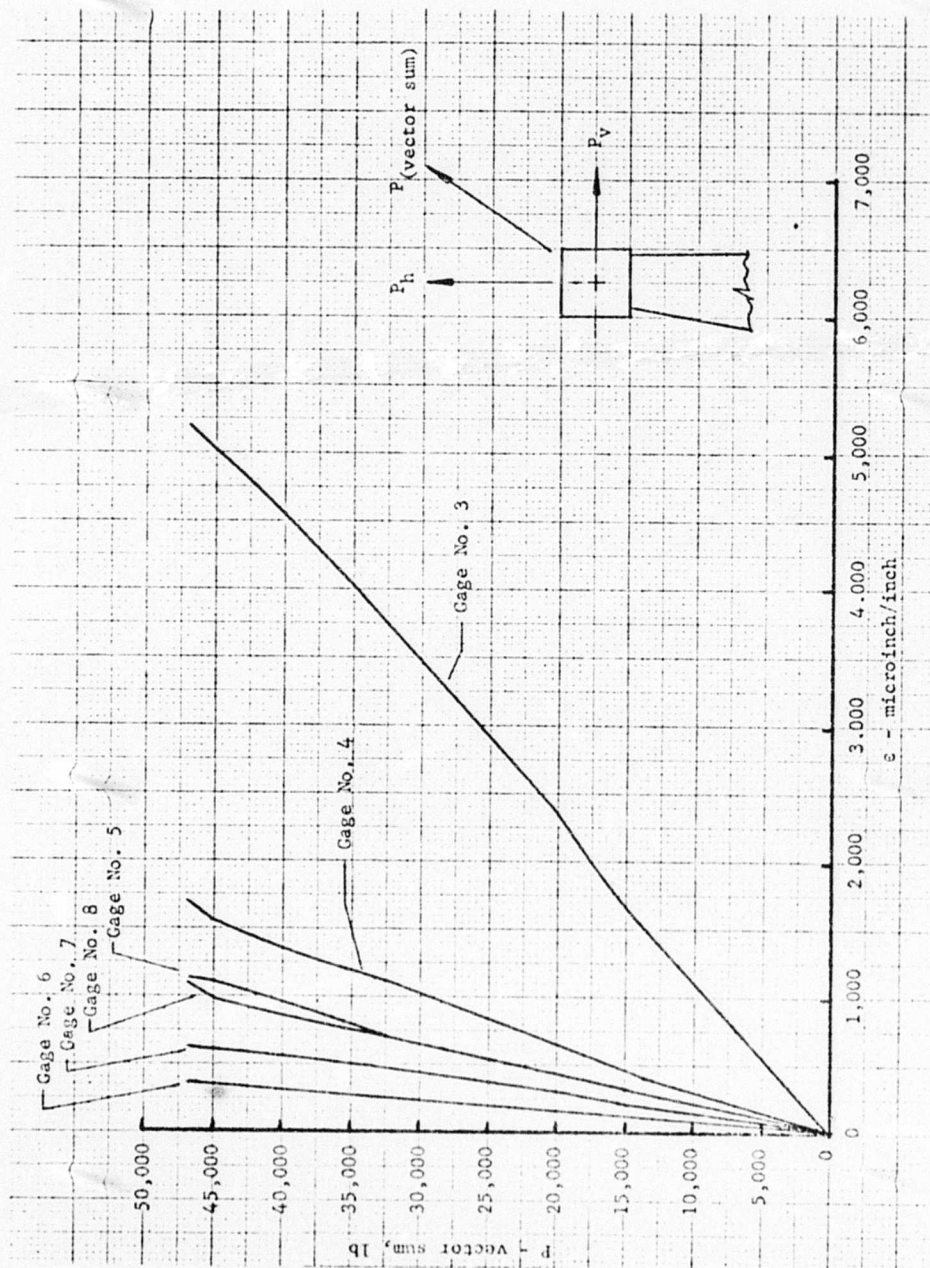
45
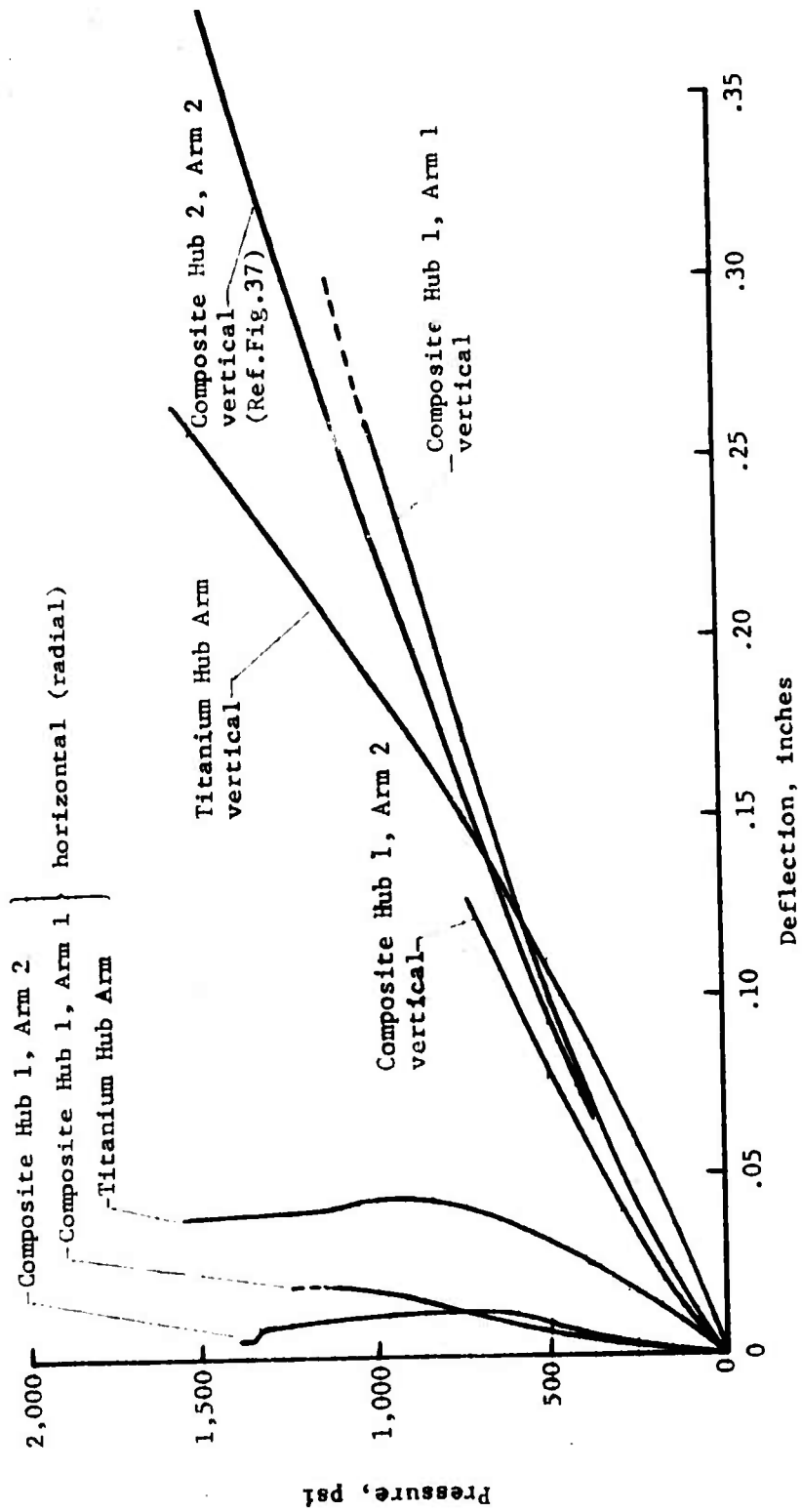
Figure 27. Strain Development, Hub 1, Arm 1.

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Figure 28. Deflection of Hub Reference Point.

The correction was made by reinforcing the bond between the flanges of the shear box and the lower plate by means of bolts and outside doublers. It was further concluded that this modification did not represent a design change but only a necessary fix to compensate for poor-quality bond and that a better bond could be achieved by changes of the adhesive system and fabrication procedures to be implemented on any future hubs. The reinforced joint is shown in Figure 29. The related stress analysis begins on page 215 (sheet 141 of Appendix 1).

This correction was incorporated only on those three arms of hub no. 2 which were expected to be tested under vertical loads. Prior to installation of the bolts, additional adhesive was injected into the bond line. The reinforcement of the arms is shown in Figure 30.

The above decision resulted in having to test one hub with a reduced structural integrity and the other with an improved structural integrity. Therefore, the original test plan was modified as follows:

Hub No. 1 - Fatigue test, low stress/high cycle. After completion of required 1×10^7 cycles, or after failure prior to achieving them, the hub shall be loaded to static ultimate until failure or until limitation of test equipment is reached. Should the hub fail prematurely under cyclic vertical load, the tension loops shall be loaded to failure or to equipment limitation.

Hub No. 2 - (a) Fatigue test, high stress/low cycle, conducted on one arm up to 1×10^4 cycles; (b) static loading to failure or to equipment capability, conducted on a different arm; (c) fatigue test, low stress/high cycle, conducted on a third arm. This latter test was to be considered only if the required time under load (278 hours) of the first hub was significantly reduced due to premature failure.

Low Stress/High Cycle Test on Hub No. 1

A second pair of arms was strain gaged as shown in Figure 26, and dial indicators were installed as before. To check out the system and the reaction of the hub, a low-stress test was first conducted in which the horizontal load was increased to 13,000 lb and the vertical to 8,630 lb. The vertical load was then dropped to zero, maintaining the horizontal load. After this, the horizontal load was also removed. With the exception of very low level cracking noises, no sounds were audible. The hub was then tested to the maximum low-stress-cycle load. The load was applied at a constant ratio until 43,300 lb horizontally and 17,260 lb vertically were reached. Then, by maintaining the horizontal load, the vertical load was manually cycled three times from maximum to zero. During the first cycle the hub developed some low-level cracking noises. In the following
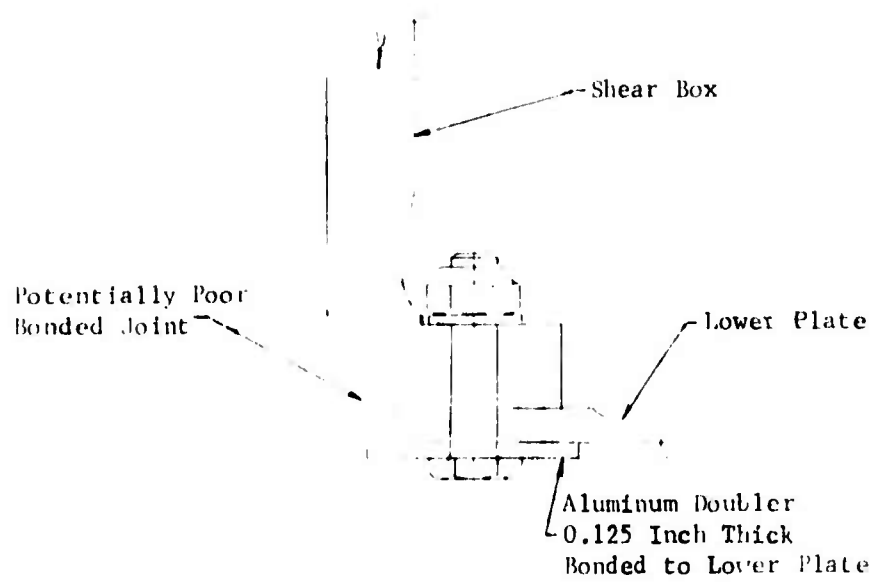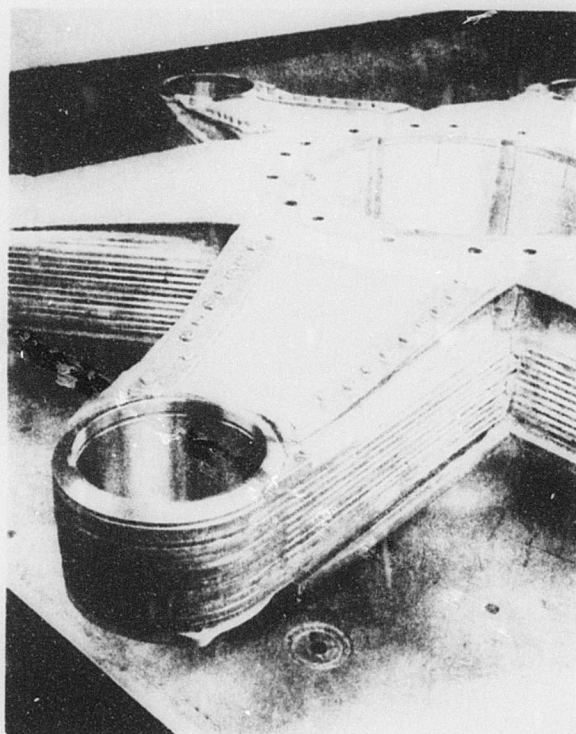
48

Figure 29. Bolt Location.

Figure 30. Corrected Joint.

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cycles the hub remained quiet, indicating that some peak stresses had been relieved. Finally, the automatic cycling system was connected and the prescribed loads were applied. Under this load condition the horizontal load remained constant at 43,300 lb and the vertical load was cycled between +17,260 lb (up) and -5,780 lb (down). The duration of one cycle was dictated by equipment capability and was determined to be one cycle per 8 seconds.

In the original test plan, an assumption was made that a cycling speed of one cycle per second would be possible. The test plan also had the provision that in case the duration of one cycle was longer, the number of cycles could be reduced; however, the total time under load should remain identical to that of the test plan. As the actual cycle duration was 8 seconds, the total number of cycles for the low-stress load condition was modified to 125,000 under this provision of the test plan. This was equivalent to a total of 278 hours under load. The actual duration of the test effort was close to 420 hours, which included interruption of cycling, downtime for equipment maintenance, and correction of some test equipment problems that were detected early during the test. After completion of the cycle test, the hub arm was loaded to fail statically. Failure occurred at 73% of limit load. The mode of failure and the probable cause were the same as described previously (p. 43). In accordance with the modified test plan, the hub was then loaded only radially, without any sign of failure. After reaching the ultimate load, the pressure was held for 3 minutes. The test was discontinued after a 3200-psi pressure (test equipment limitation) was reached. At this point the hub withstood 123% of the ultimate static design load. Deflection readings are plotted in Figure 28; strain gage readings, in Figures 31 and 32.

The hub arm was then again subjected to the combined radial and vertical load. At 1000 psi vertical cylinder pressure (23,3)5 lb or approximately 63% of limit load), the test was discontinued due to excessive vertical deformation of the hub arm.

Strain gage readings were taken at the beginning of the test and then at longer intervals during the test. It was expected that the repeated loading would cause some reduction of the composite modulus of elasticity and therefore some increases in strain with increasing number of cycles. The strain gage readings are plotted in Figure 31 for gage nos. 3, 6, 7, and 8 after completion of the following cycle nos: 4, 18,500, 50,000, 100,000, and 125,000. Examination of curves in Figure 31 did not reveal the expected trend. On the contrary, the strain gage behavior appears to be random, and some readings indicate a smaller total strain at large cycle numbers than at small cycle numbers. In order to find a strain pattern, the maximum strain reading was plotted as a function of the completed cycles. This relationship is presented in Figure 32 for three selected strain gages: nos. 3, 7, and 8. As shown in Figure 26,
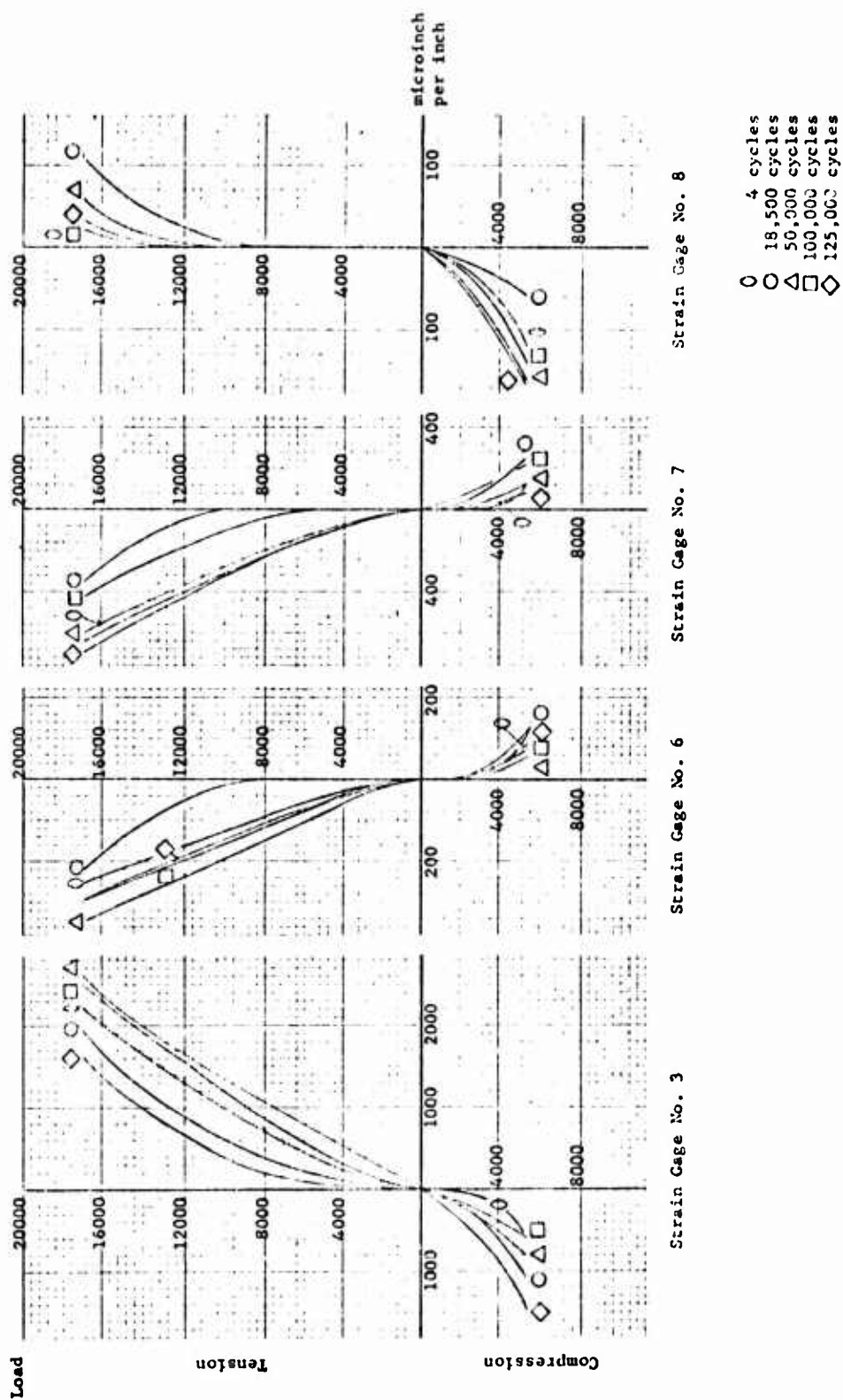
51

Figure 31. Strain Development During Cyclic Test, Hub No. 1, Arm 2.

52
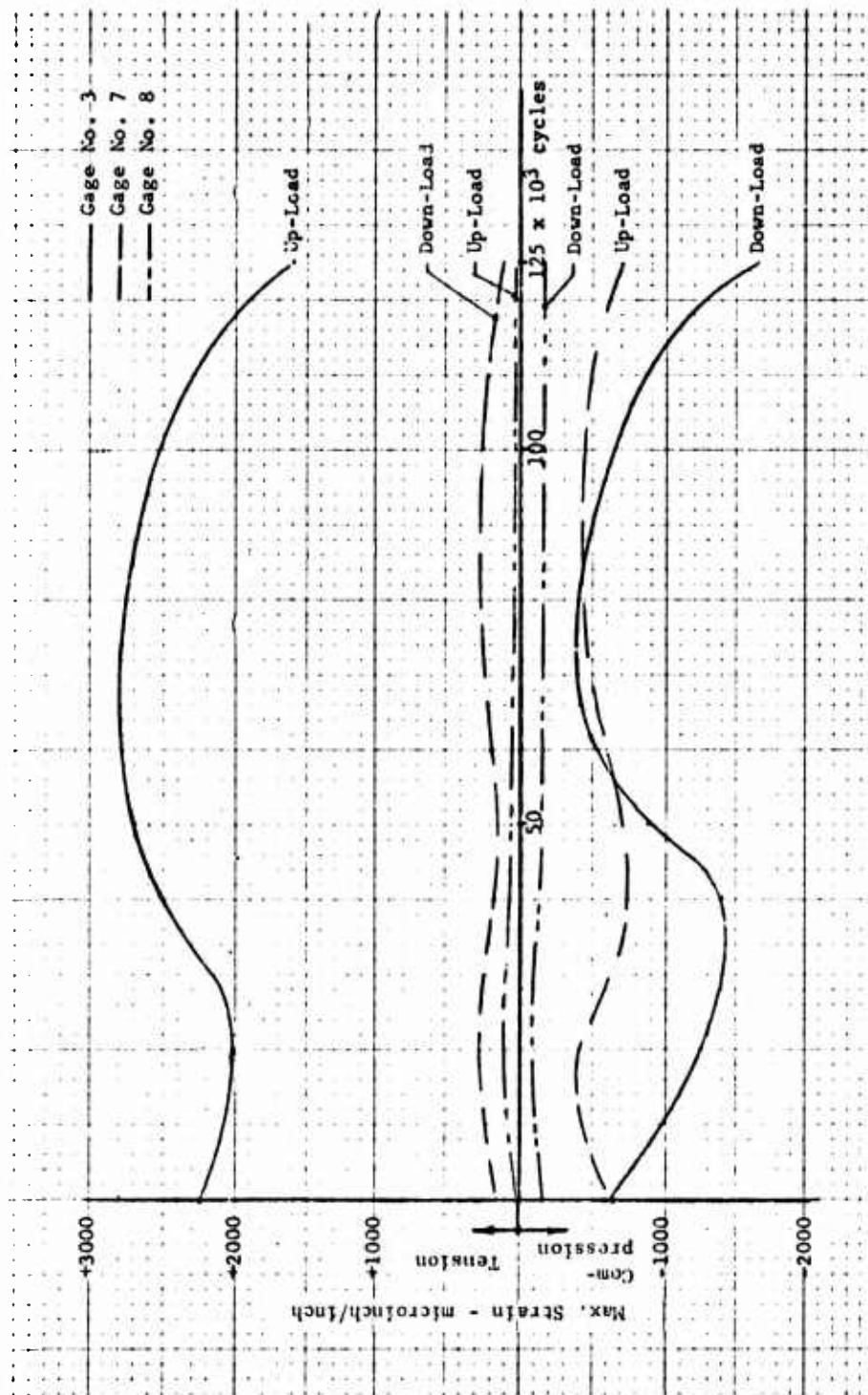
Figure 32. Change of Maximum Strain With Increasing Cycles, Hub No. 1, Arm 2.

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these strain gages are located on the bottom plate (no. 3), on the top plate (no. 7), and close to the neutral axis (no. 8). When the maximum up-load was applied, it was expected that the predominant strain would be as follows:

Gage no. 3 - large tensile strain values

Gage no. 7 - compression strain value;

Gage no. 8 - small strain values

The curves in Figure 32 confirm these expectations but show also an unexpected fluctuating pattern. This pattern shows that with increasing cycle numbers, the magnitude of the maximum tension strain decreases or increases as the compressive strain increases and decreases such that the total strain magnitude (tension plus compression) remains essentially constant. This absolute strain value for the three gages is approximately

Gage no. 3 - .00300 in./in.

Gage no. 7 - .00065 in./in.

Gage no. 8 - .00015 in./in.

The reason for this behavior is unexplained; however, the pattern indicates a cyclic shifting of the neutral axis, which may be caused by stiffness changes within the composite structure. It should be noted that gage no. 3 recorded a marked increase in compressive strain (upper plate) at high cycle numbers in spite of the constantly present radial tension load. This may confirm that the structure is critical for vertical loads, and if the test had continued, the hub might have failed at higher cycle numbers in compression.

High Stress/Low Cycle Test on Hub No. 2

Initial high stress/low cycle tests were conducted on one arm of hub no. 2 by manual control. In accordance with the test load requirements, the loads were applied at a radial to vertical ratio of 1.5 : 1. During the first cycle, the hub developed some cracking noises which disappeared during subsequent cycles. After completion of manually operated cycles, the system was programmed for automatic cycling. In order to simplify pressure control and to assure that the maximum radial load was reached simultaneously with the maximum vertical load, the system was pressurized by one pressure source. Therefore, the ratio between the radial and vertical loads was controlled by the ratio of the piston area of the hydraulic cylinders. This ratio deviated somewhat from the 1.5 : 1 desired and was actually 1.34 : 1. Since the vertical load was considered the most critical, its magnitude was kept as required by the test plan, namely, 36,500 lb limit. The radial load was reduced from 55,120 lb to 49,135 lb. This slight reduction of the radial load was believed

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not to affect the verification of the structural adequacy of the hub
because the tension loops of the hub structure which support this
load have a very large safety factor against failure. The cyclic
duration was 15 seconds from zero load to maximum and back to zero.
After 170 cycles, the hub started to develop some cracking noises
which increased in their intensity. The cycle test was terminated
after completion of 186 cycles, at which time the lower plate laminate
failed by tear-out at the most inward bolts of the aluminum doublers.
This failure is shown in Figure 33. During the high stress cyclic
test, readings of the maximum vertical hub arm deflection were taken
periodically. The recorded values are plotted in Figure 34. They
show that the deflection increased progressively with the number of
cycles from 0.36 inch at the beginning of the test to 0.57 inch at
186 cycles, when the reading was taken just prior to failure after
the 188th cycle.

Static Ultimate Test on Hub No. 2

This test was conducted on a second pair of arms of hub no. 2 which
were not affected by the failure of the high-stress-cycle test. This
arm was strain gaged similar to hub no. 1, except that gage no. 3 was
placed 2.20 inches from the edge and not 0.63 inch as shown in
Figure 26. The load was applied by manual control of the pressures
for the radial and vertical cylinders so that the required radial to
vertical load ratio of 1.5 : 1 was kept constant. The load was
applied in 10% increments of the ultimate design load per pressure
schedule listed in Table VI.

During the test, the following types of parameters were recorded or
observed:

- Pressures in the vertical and horizontal cylinders

- Vertical and horizontal deflection of the reference point

- Strain at six locations

- Cracking noise intensity

- Visible changes

The noise intensity was arbitrarily defined by

A - low

B - medium

C - severe
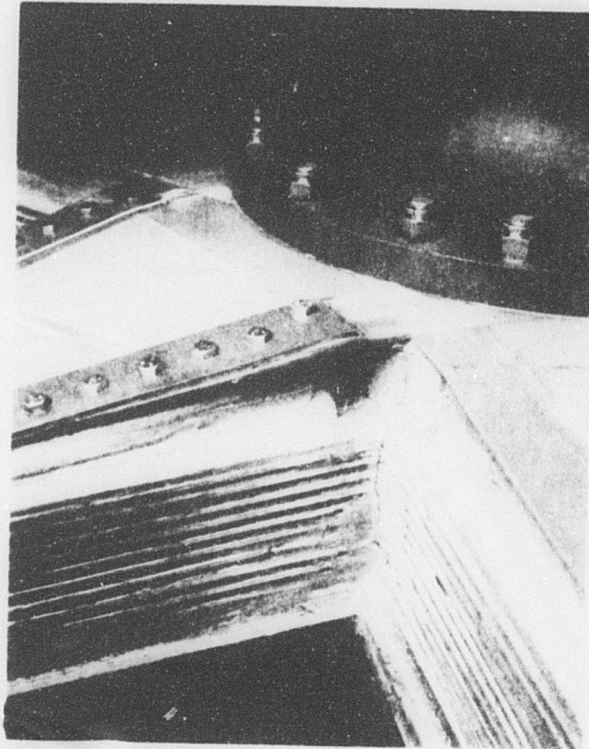
Figure 33.   Hub No. 2, High-Stress-
             Cycle Failure.

56
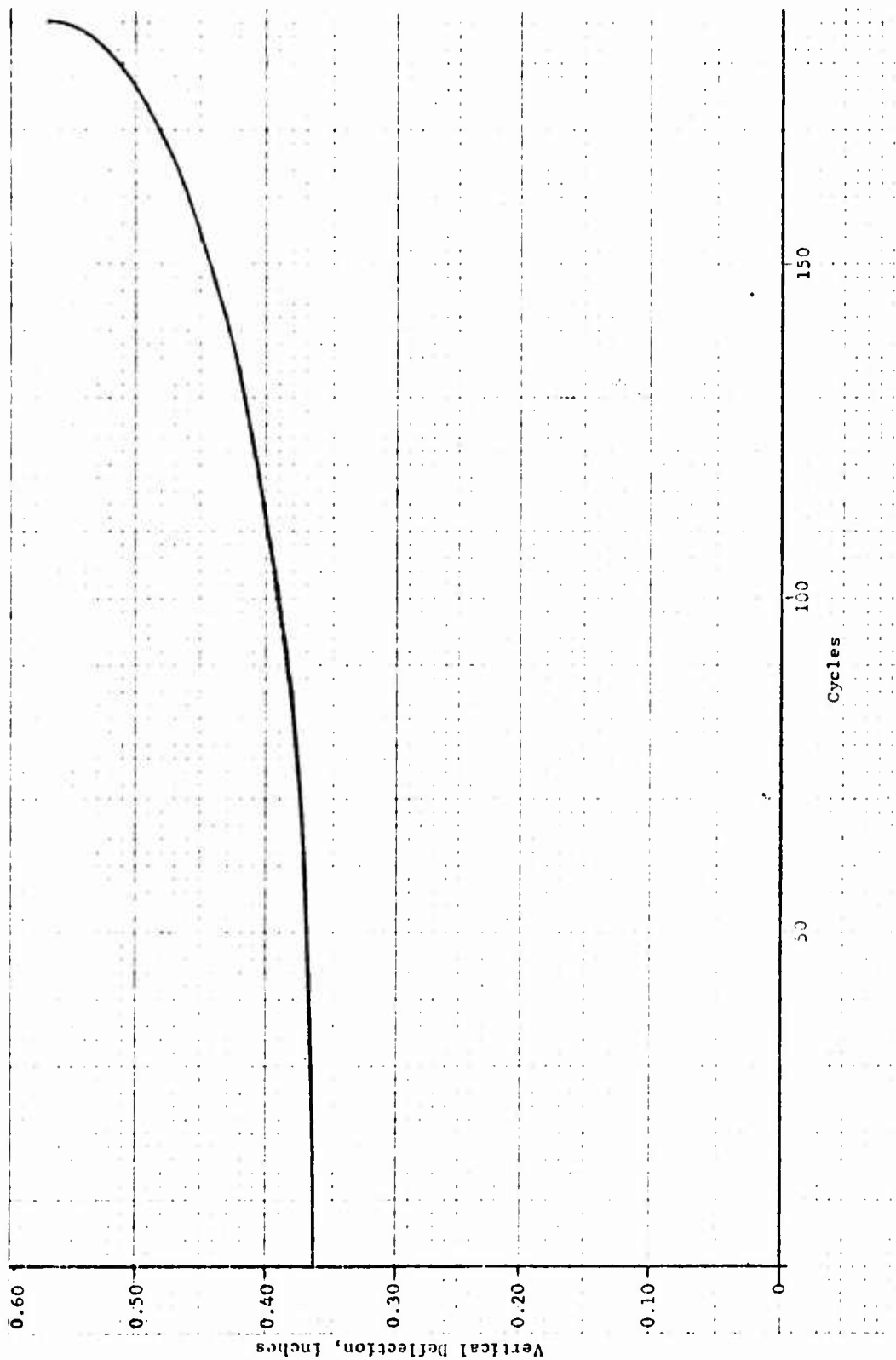
Figure 34. High-Stress Fatigue Maximum Vertical Deflections.

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TABLE VI. TEST PRESSURE SCHEDULE					
		Vertical		Horizontal	
Increment	% Ultimate	(psi)	(lb)	(psi)	(lb)
(1)	10	234	5480	263	8267
(2)	20	468	10960	526	16534
(3)	30	702	16440	789	24801
(4)	40	936	21920	1052	33068
(5)	50	1170	27400	1315	41335
(6)	60	1404	32880	1578	49602
(7)	70	1638	38360	1841	57869
(8)	80	1872	43840	2104	66136
(9)	90	2106	49320	2367	74403
(10)	100	2340	54800	2630	82670

The following observations were made as the load was increased from one increment to the next:

1. none

2. noise intensity A

3. noise intensity B

4. noise intensity B; resin crack in corners between tested and adjacent arms

5. noise intensity C; resin crack in corners opens up and progresses vertically

6. noise intensity C; progressive crack growth

7. noise intensity C; vertical crack in corners 0.10 inch wide; aluminum doubler end sheared from lower plate and moved 0.05 inch

8. noise intensity C, vertical crack in corners opens up at the bottom approximately 0.20 inch; aluminum doubler shears from lower plate approximately 0.15 inch; lower plate fails in tension-shear locally at the ends of the aluminum doubler (see Figures 35 and 36)

After this failure, the vertical load capacity was exhausted, and the pressure level in the vertical cylinder dropped to increment no. 6 (32,880 lb). The pressure was blocked in the vertical cylinder at this level, and the load in the radial direction was increased to ultimate design load with the following observations at increments:

7. none

8. none

9. noise intensity A, coming from the failed area corners

10. noise intensity C, coming from the failed area corners

Testing was discontinued after the ultimate load was reached in the radial direction. At this instant, the hub arm had supported 82,670 lb radially and 33,879 lb vertically in spite of the failure that occurred at pressure increment no. 8.

Figure 37 represents the deflections of the reference points. At failure load, the vertical deflection was 0.976 inch and remained as permanent set after the loads were returned to zero. The radial deflection was initially very small and even negative, probably due to the large vertical deformation. It increased, however, after pressure increment no. 7 and

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Figure 36. Hub No. 2, Static Load
Failure, Detail, Right
Side.

Figure 35. Hub No. 2, Static Load
Failure, Left Side.

60
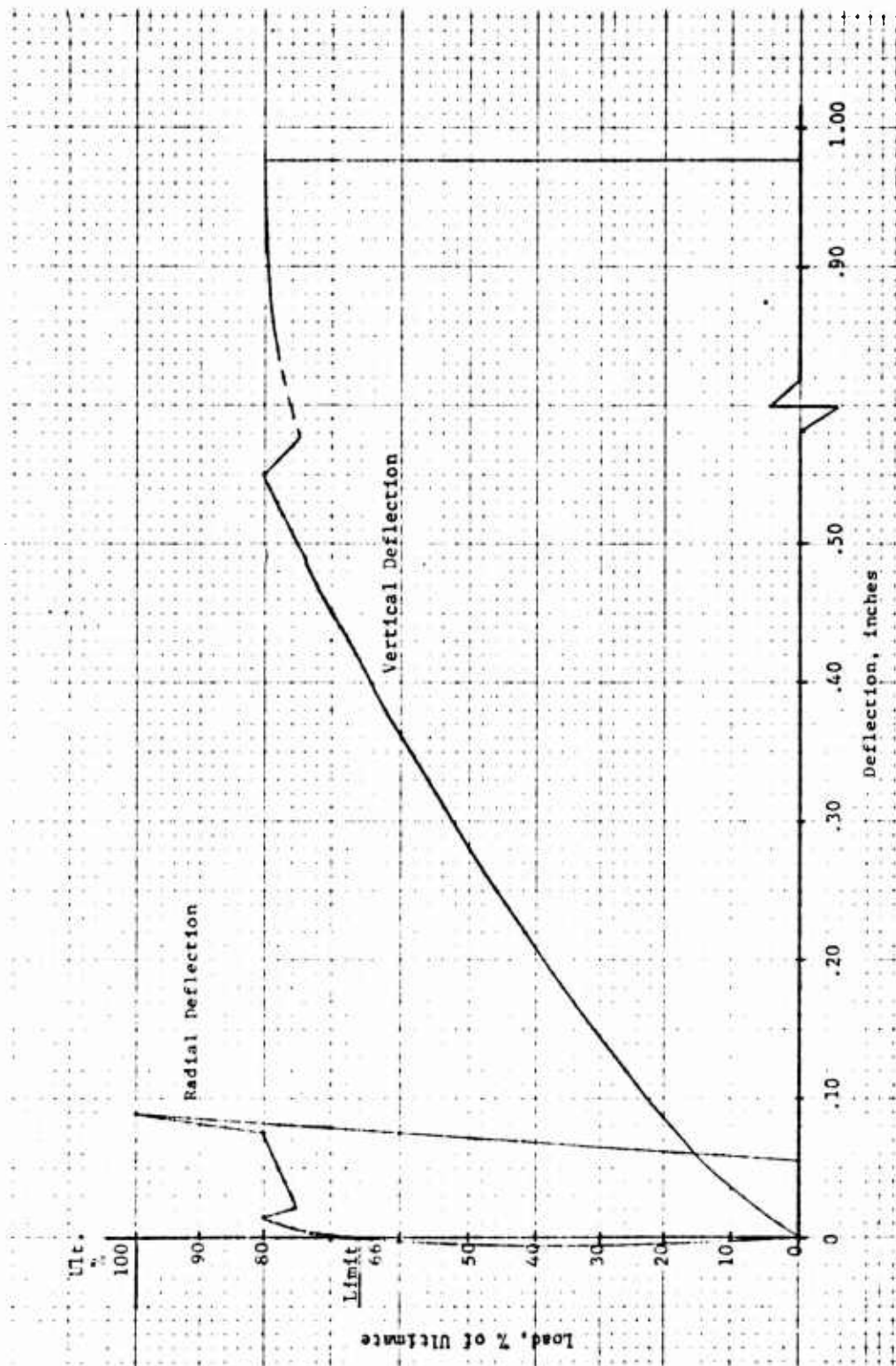
Figure 37. Deflection of the Reference Point,
Hub No. 2 Static Test, Arm 2.

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reached a maximum value of 0.089 inch. The permanent set in the radial direction was only 0.055 inch. The strain gage behavior is shown in Figure 38. The strain development was normal up to 40,000 lb resultant (vector sum) load, which corresponds to the end of the fourth pressure increment. At this point (which coincided with observed resin cracks in the hub corners) a strain arrangement took place, and most gages behaved nonlinearly up to the partial failure after increment no. 8 was reached. The gages then behaved erratically, but continued to record strain during load increase in the radial direction. It should be noted that gage no. 4 (diagonal shear) dropped out at pressure increment no. 5. A possible reason is seen in debonding of the gage from the side surface of the hub arm. It should further be noted that gage no. 3 showed the largest strain and was essentially linear up to the failure load. In this respect it behaved very similar to gage no. 3 of the first hub (see Figure 27). Strangely enough, it recorded less stiffness of the structure than that of the first hub. The first hub gage no. 3 is also plotted in Figure 38 for comparison purposes. Explanations may be sought in the difference of this respective location (distance from the arm edge).
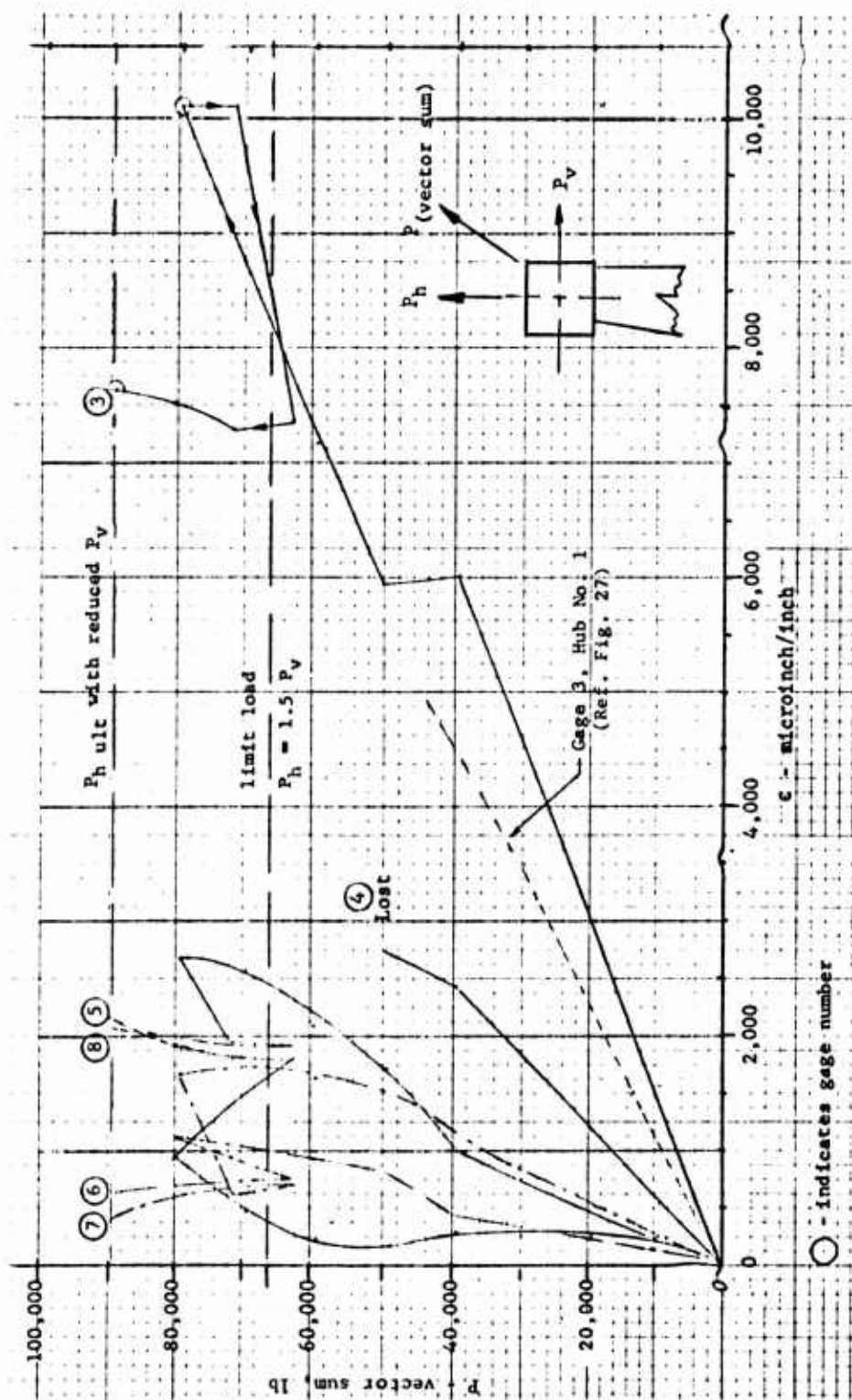
Figure 38. Strain Development Static Test, Hub No. 2, Arm 2.

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CONCLUSIONS

Whittaker R&D has conceived a novel design of a large helicopter rotor hub using fiber reinforced plastic. A structural analysis for selected load conditions was prepared, and two hubs were constructed and ground tested. The experience gained in conducting this program is a valuable asset for any further improvement and development of composite helicopter rotor hubs. This experience with the present design leads to the following principal conclusions:

1. It is feasible to construct helicopter rotor hubs from fibrous composite materials without any limitation of the hub size.

2. The filament-wound loops are very reliable and effective elements for resisting centrifugal (radial) forces. The radial elongation under load can be kept equal to or less than the elongation of a hub made from titanium metal.

3. The resistance to vertical (lift) forces of the present hub design is not adequate, and concepts should be sought to improve strength and decrease deflection.

4. The centrifugal and vertical loads are taken by different material components which are optimized for tension and for shear, respectively. This results in increased weight if compared with a metal hub, where those loads are carried by the same homogenous material. However, the relative weight penalty will probably decrease with increasing hub sizes.

5. The present design of some details resulted in assembly operations which seemed to be excessively time-consuming. Such operations were the layup of the shear boxes and the fit of the shear tapes between the loops and the shear boxes. A number of details, such as wound loops and molded spacers, required rework to provide a better fit in assembly.

6. The resin system and the adhesive material to be used should not be of the brittle type. They should be tough and peel resistant at an adequate pot life to permit a single cure of the total assembly, especially for better resistance to cyclic loads.

7. Attention should be given to detail design to avoid strain incompatibility and difficult fitting operations at assembly. For increased reliability, introduction of loads into the hub structure should not depend on adhesive strength only but utilize help by positive mechanical devices.

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8. When the presently recognized design problems have been worked out, the composite hub will not be difficult to fabricate by using adequate production-type tooling and manufacturing methods.

9. Since the composite design consists of prefabricated elements which can be individually inspected for quality, the overall reliability of the composite hub should be high.

10. The multiple load path, which is typical for fibrous composite structures, offers a high ballistic tolerance and fail-safe characteristics. Tests conducted with the prototype hubs have demonstrated that even after failure, a significant load-carrying capability remains.

11. Based on the cost for fabrication and materials of the prototype hubs of the present design, it is estimated that the cost of hubs in production quantities (90% learning curve) will be approximately:

100	-	$13,000 each
500	-	$11,300 each
1000	-	$10,900 each

This compares favorably with the reported cost of the present titanium hub of $15,000. Design and fabrication improvements may reduce the price even more.

RECOMMENDATIONS

It is recommended that an engineering development and testing program be conducted for design optimization of the composite helicopter rotor hub and for its evaluation under flight conditions. In particular, the following tasks should be carried out.

1. The present composite hub should be redesigned to eliminate recognized deficiencies and to implement structural improvements.

   a. The transfer of the vertical shear load should be improved and the shear deflection minimized by improving the shear load transfer from the shear box to the hub center, and by possible addition of exterior shear webs. For improved shear stiffness, material other than glass fiber composites, such as graphite fiber composites or thin metallic webs, should be considered.

   b. The hub center section should be designed for a more reliable torque transfer and strain compatible transfer of tension between the opposite hub arms and crossing tension loops of adjacent arms. The introduction of shear and bending loads from the individual arms to the hub center section should also be optimized.

   c. The introduction of vertical down-load into the lug should be accomplished by means of a retention ring similar to the present bushing flange for introduction of vertical up-loads.

   d. The transfer of shear and bending forces from the lug area into the shear box and tension loop structure should be designed to result in improved strain compatibility.

   e. The bending mode of the arm should be closely analyzed, the effective neutral axis for the critical load conditions determined, and the design of the top and bottom plates made to reflect the optimum stress distribution, thus preventing tension failures of the bottom plate.

2. The hub design should be made compatible with production manufacturing procedures by reducing steps requiring manual labor and dependence on the skill of the fabricator.

   a. Design of all tools should be based on production principles, reproducibility of components, and lowest possible fabrication cost.

   b. In several instances the design must be subordinated to ease and reliability of production. This would include also the production-oriented selection of resin binders and adhesives.

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c. Great care should be taken to produce accurate mating surfaces required for reliable bonding at assembly with no or minimum assembly fit work.

d. The fabrication time of the shear boxes should be drastically reduced by design modification as well as by selection of materials and of manufacturing methods. An automated or a semiautomated laminating and molding process should be considered.

e. The material cost of the shear tapes and the labor involved for their assembly into the hub structure is relatively high. Therefore, design and material changes should be considered.

f. The cost of unidirectional glass fiber tape is high (approximately 50% of all nonmetallic materials). Also high is the cost of the metallic hub center (64% of all metallic parts). Therefore, a material substitution should be investigated and the geometric complexity of the hub center eliminated.

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APPENDIX I
STRESS ANALYSIS

This appendix includes the following items:

Cruise Condition Fatigue Life - Shear, Sheet No. 136

"CAC" Condition Fatigue Life - Shear, Sheet Nos. 138 and 140

Revised Attachment, Sheet 141

DISCUSSION

The composite helicopter rotor hub is analyzed for the loads specified in Whittaker Research and Development Report SDE-72-2.[13] Both static and fatigue loading conditions are considered.

Two cross sections of the hub arm are analyzed for shear, moment, and axial loads. Section A-A (see page 78) is located 10.9 inches outboard of the hub center line. Section B-B (see page 115) is located 19.9 inches out-board of the hub center line. The filament-wound straps, which encircle the bearings at the vertical hinge 24 inches outboard of the hub center line, are analyzed for tangential and radial stresses by the methods developed in USAAVLABS Technical Report 69-25.[2]

In the latest design concept, the bearing geometry was revised. Bearing "A" (see page 135) is now located on top. This design change decreases the magnitude of R_A and decreases bending moments in the hub arms. The stress analysis prior to page 135 is not corrected for the revised bearing geometry and is therefore conservative. The stress analysis following page 135 includes the effects of the bearing geometry change.

In the course of prototype fabrication, some design changes were made to accommodate fabrication processes. An addendum to the stress analysis, beginning on page 182, was written to examine the effect of these design changes on hub stresses. The addendum also includes the analysis for a low-cycle, high-stress fatigue regime.

ALLOWABLE STRESSES

The allowable stresses for the 1581 E-glass/epoxy laminates are obtained from MIL-HDBK-17.[3] These allowable stresses are multiplied by a 0.9 heat factor to account for possible structural temperatures of 160°F. Allowable stresses for the filament-wound S-glass laminates and for the Scotchply S-glass unidirectional laminates are assumed to be:

$$0° \text{ to Fiber, } F_{tu} = 180,000 \text{ psi at } 160°F$$

$$90° \text{ to Fiber, } F_c = 25,000 \text{ psi at } 160°F$$

Subsequent testing of filament-wound strap test specimens at Whittaker R&D gave much higher values for allowable stresses than those values shown above. The interaction equation at failure (Reference USAAVLABS Technical Report 69-25[2]) is

$$\mu = 1.0 = \frac{1}{\left[\left(\dfrac{\sigma_r}{\sigma_r^*}\right)^2 - \dfrac{\sigma_r \, \sigma_\theta}{\sigma_r^* \, \sigma_\theta^*} + \left(\dfrac{\sigma_\theta}{\sigma_\theta^*}\right)^2\right]^{\frac{1}{2}}}$$

where σ_r =   Applied Radial Compression Stress

σ_θ =   Applied Tangential Tensile Stress

$\sigma_r^* = F_{c_{90°}}$ =   Allowable Radial Compression Stress

$\sigma_\theta^* = F_{tu_{0°}}$ =   Allowable Tangential Tensile Stress

By substituting values for the test failure load and test specimen geometry into the interaction equation and assuming that $\sigma_r^*/\sigma_\theta^*$ = 25,000/180,000 , calculated allowable stresses are

$$F_{tu_{0°}} = 328,500 \text{ psi}$$

$$F_{c_{90°}} = 45,600 \text{ psi}$$

Although these calculated allowables are based on a minimum value from three test specimens, these allowable stresses were not used. The values assumed on page 71 were used in this report. As a result, an additional margin of safety exists on the unidirectional S-glass structure above that shown in this report.

Adhesive bond allowable shear stress is based on Whittaker R&D test data:

$$F_s = 6,500 \text{ psi}$$

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			TABLE VII.	MINIMUM MARGINS OF SAFETY AS CALCULATED			

Location	Item	Load Condition	Type of Stress	M.S.	Sheet No.	Page No.
			ORIGINAL CROSS SECTIONS			
Section A-A	Lower Plate	TW 7F2	Tensile	+0.13	12	84
Section A-A	Upper Plate	TW 7F2	Compression Buckling	+0.13	15	87
Section A-A	Web @ N.A.	TW 7F2	Shear	+0.18	17	89
Section A-A	Upper Plate	TW 7F2	Shear	+0.018	23	95
Section A-A	Lower Plate	TW 7F2	Shear	+0.11	24	96
Section A-A	Upper Plate	TW 7F1	Shear	+0.024	39	111
Section B-B	Lower Plate	TW 7F2	Tensile	+0.06	48	120
Section B-B	Upper Plate	TW 7F2	Compression Buckling	+0.10	51	123
Section B-B	Web @ N.A.	TW 7F2	Shear	+0.06	53	125
Section B-B	Upper Plate	TW 7F2	Shear	+0.09	59	131
Lug	Upper Strap	TW 7F2	Combined Tangential and Radial	+0.65	65	137
			REVISED CROSS SECTIONS AND BEARING GEOMETRY			
Section A-A	Lower Plate	TW 7F2	Tensile	+0.46	120	192
Section A-A	Upper Plate	TW 7F2	Compression Buckling	+0.87	121	193

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TABLE VII - Continued						
Location	Item	Load Condition	Type of Stress	M.S.	Sheet No.	Page No.
REVISED CROSS SECTIONS AND BEARING GEOMETRY - Continued						
Section A-A	Upper Plate	TW 7F2	Shear	+0.21	122	194
Section B-B	Lower Plate	TW 7F2	Tensile	+1.16	126	198
Section B-B	Web @ N.A.	TW 7F2	Shear	+0.68	128	200

NOTE: On the following hand-written pages of this appendix the stress analyst made numerous references to other page numbers of the appendix. These page numbers, however, refer to the sheet numbers in the lower right-hand box of each page, and not to the report page number at the bottom center.

COMPOSITE HELICOPTER ROTOR HUB~

COND. TWIFE ~ SYM. ONE & PULLOUT (AUTO)
IS MAX.

SEE NOTE PAGE 3
& ADDENDUM PAGE 108

$b = 12.90$
$a = 9.39$
$c = 5.37$

$T_G = 110,000$ # LIMIT
$V_G = 0$

$V_N = 36,500$ # LIMIT
$M_G = 72,000$ # LIMIT
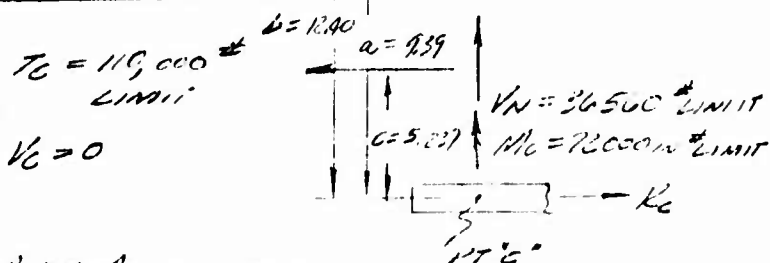
HUB REM AXIAL LOAD:

$$T_{G_{TOT}} = T_G + \frac{M_G}{h} \quad , \quad h = \text{MOMENT ARM TO DAMPER} = 9.412 \text{ IN}$$

$$= 110,000 + \frac{72,000}{9.412}$$

$$= 117,650 \text{ # LIMIT}$$

FROM TIMKEN ENG. JOURNAL SECT 2, PGS 156 & 159:

$$K_a = 1.24$$
$$K_L = 1.61$$

FROM $\Sigma M_{PT\,G}$:

$$(R_A + L_B)\left(\frac{a+b}{2}\right) = T_{G_{TOT}}(c)$$

$$R_A + R_B = \frac{117,650 (5.37)(c)}{18.90 + ...} = 50,552$$

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COMPOSITE HELICOPTER ROTOR HUB

$$\frac{0.47(K_A + K_C)}{K_C} = \frac{0.47(56552)}{1.24} = 21435$$

$$V_N = 36560 > 21435$$

R_B is 0 (REF. TIMKEN ENGINEERING JOURNAL, SECTION 1, Pg. 13-7)

$$K_A = \frac{117650(5.233)}{9.39} = 65616 \,\#\, LIMIT$$

$$K_C = T_{C_{TOT}} - K_A = 117650 - 65616$$
$$= 52034 \,\#\, LIMIT$$

MJO NO	SUBJECT			DATE	CHECKED BY
5027-001				10/12/71	
TASK NO				CALCULATIONS BY	SHEET NO.
				A.M.T.	2

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COMPOSITE HELICOPTER ROTOR HUB

NOTE~

THE BEARING GEOMETRY WAS REVISED
IN A LATE DESIGN REFINEMENT.
BEARING "A" IS NOW LOCATED ON TOP.
THIS DESIGN CHANGE DECREASES THE
MAGNITUDE OF R_A AND DECREASES
BENDING MOMENTS IN THE HUB ARMS.
REVISED GEOMETRY IS SHOWN ON
PAGE 61. THE REVISED VALUE FOR
R_A FOR COND. TW7F2 IS:

$$R_A = 55110 \text{ LBS. LIMIT}$$

THE FOLLOWING ANALYSIS UP TO PAGE 61
NEGLECTS THE REDUCTION IN R_A AND
IS THEREFORE CONSERVATIVE.

MJO NO		SUBJECT				DATE 12/14/71	CHECKED BY
TASK NO						CALCULATIONS BY A.M.T.	SHEET NO. 3

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COMPOSITE HELICOPTER ROTOR HUB (CONT.)

SECTION A-A (10.9 IN OUTB'D OF HUB ₵)

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COMPOSITE HELICOPTER ROTOR HUB~(CONT.)

BOTTOM STRAP (ITEM ⑦)

ASSUME STRAP IS 8 PLIES 1581 @ ±45°, t = .072

+ 20 PLIES SCOTCHPLY, t = $\dfrac{.150}{.222}$

FOR ITEM ⑪ ASSUME

$$E = \dfrac{t_{45} \, E_{1581}_{\pm 45} + t_0 \, E_{0 \,(SCOTCHPLY)}}{t_{TOT}}$$

$$= \dfrac{.072 \left(2.2 \times 10^{6}\right) + .150 \left(6.8 \times 10^{6}\right)}{0.222}$$

$$= 5.3 \times 10^{6} \, psi$$

STRESS-STRAIN CURVE FOR 1581/EPOXY AT
± 45° IS NON-LINEAR. THEREFORE,
ASSUME FAILURE OCCURS AT FAILING
STRAIN OF SCOTCHPLY.
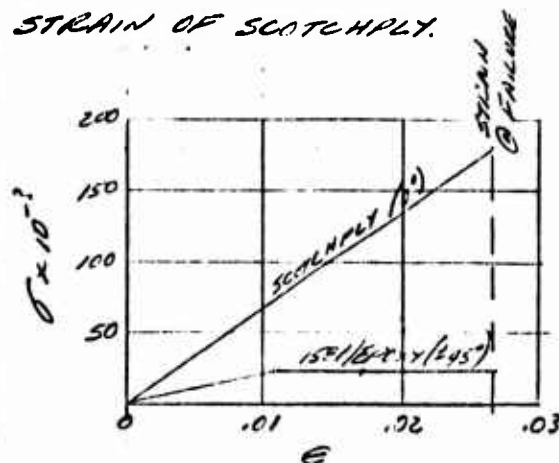
MJO NO 3027-001	SUBJECT		DATE 10/18/71	CHECKED BY
TASK NO			CALCULATIONS BY A.M.T.	SHEET NO. 5

COMPOSITE HELICOPTER ROTOR HUB (CONT.)

ALLOWABLE TENSILE STRESS IN BOTTOM
STRAP (ITEM ⑫) @ STRAIN TO FAILURE:

$$F_{TU} = \frac{t_0 \, F_{TU_0} \, (\text{SCOTCHPLY}) + t_{45} \, F_{T_{45°}} \, (1591 \, PLIES)}{t_{TOT}}$$

$$= \frac{.150 \, (180,000) + .072 \, (24,000)}{0.222}$$

$$= 129,000 \, psi$$

$F_{T_{45}} = 0.9 \, (26,600)$

$= 24,000 \, psi$ @

$160°F \, (1591 \, PLIES)$

$F_{T_0} = 180,000 \, psi$

@ 160°F (SCOTCHPLY S GLASS)

BOTTOM PLATE (ITEM ⑮)

ASSUME STRAP IS 8 PLIES 1591 @ ±45°, t = .072

+ 6 PLIES SCOTCHPLY, t = .045

$t_{TOT} = 0.117$

$$E = \frac{.045 \, (6.8 \times 10^6) + .072 \, (2.2 \times 10^6)}{.117}$$

$$= 3.9 \times 10^6$$

$$F_{TU} = \frac{.045 \, (180,000) + .072 \, (24,000)}{.117}$$

$$= 84,000 \, psi$$

MJO NO 3027-001	SUBJECT		DATE 10/13/71	CHECKED BY 5
TASK NO			CALCULATIONS BY A.M.T.	SHEET NO. 6

COMPOSITE HELICOPTER ROTOR HUB (CONT.)

TOP PLATE (ITEM (13))

ASSUME PLATE IS 9 PLIES 1581 0 ±45°

$$t = 0.081$$

+ 19 PLIES SCOTCHPLY, t = 0.143

$$t_{TOT} = 0.224$$

$$E = \frac{.143(6.5 \times 10^6) + .081(2.2 \times 10^6)}{.224}$$

$$= 5.1 \times 10^6$$

$$F_{tu} = \frac{.143(160,000) + .081(24,000)}{.224}$$

$$= 123,500 \, psi$$

COMPOSITE HELICOPTER ROTOR HUB (CONT.)

SECTION PROPERTIES — SECT. A-A

ITEM	A	E ×10⁶	AE	Y	AEY ×10⁶	AEY^2 ×10⁶	EI_0 ×10⁶
1	.075	6.8	.510	.51	.26010	.13265	.00042
2				.83	.42330	.35133	
3				1.16	.59160	.68625	
4				1.48	.75480	1.11710	
5				1.82	.92820	1.68932	
6				2.16	1.10160	2.37945	
7				2.47	1.25970	3.11145	
8				2.79	1.42290	3.96969	
9				3.13	1.59630	4.99641	
10				3.46	1.76460	6.10551	
11				3.78	1.92780	7.28708	
12	.075	6.8	.510	4.12	2.10120	8.65694	.00042
13	.229×6.05=1.355	5.1	6.912	.024	.16588	.00398	.2887
14	.314		.611	.29	.20039	.05811	.00304
15	1.458		3.208	2.68	8.59799	23.04113	5.41
16	.486	2.2	1.069	5.12	5.47385	28.02319	.0935
17	.278	5.3	1.473	5.38	7.92474	42.62570	.00603
18	.480	3.9	1.872	5.14	9.99648	53.39120	.00213
	5.271		21.345		46.49031	187.62457	5.47027

$$\overline{Y} = \frac{\Sigma AEY}{\Sigma AE} = \frac{46.49051}{21.345} = 2.178$$

$$\Sigma EI = 2\left[\Sigma AEY^2 + \Sigma EI_0 - \overline{Y}\,\Sigma AEY\right],$$

$$= 2\left[187.62 + 5.47 - 2.178(46.490)\right] \times 10^6$$

$$= 183.7 \times 10^6; \quad \Sigma AE = 2(21.345) = 42.69 \times 10^6$$

MJO NO 3027-001	SUBJECT	DATE 10/15/71	CHECKED BY ?
TASK NO		CALCULATIONS BY A.M.T.	SHEET NO 8

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COMPOSITE HELICOPTER ROTOR HUB (CONT.)

COND. TWTF2

$R_A = 65616^\#$ LIMIT

$= 98424$ LBS ULT.

$V_N = 36560^\#$ LIMIT

$= 54840$ LBS ULT.

@ N.A. AT SECTION A-A

$M = 54840 (13.1) + 98424 (1.68)$

$= 883,756$ IN$^\#$ ULT.

$P = 98424^\#$ ULT.

$V = 54840^\#$ ULT.

IF LINEAR THEORY IS USED
STRESS IN BOLT (B) IS:

$f_t = \dfrac{M y E}{\Sigma E I} + \dfrac{P E}{\Sigma A E}$

$= \dfrac{883756 (3.0)(22 \times 10^6)}{182.7 \times 10^6} + \dfrac{98424 (22 \times 10^6)}{42.67 \times 10^6}$

$E = 22 \times 10^6$ } FROM
$F_{tu} = 29,000$ psi } (B)

$y = 3.06$ IN (REF FIG. 1)

$= 37620$ psi, M.S. ~ NEGATIVE

$\epsilon = \dfrac{f}{E} = \dfrac{37620}{2.2 \times 10^{13}} = .0171$ IN/IN

JOB NO. 227-001	SUBJECT		DATE 1/15/71	CHECKED BY
TASK NO			CALCULATIONS BY A.M.T.	SHEET NO 9

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COMPOSITE HELICOPTER ROTOR HUB (CONT.)

COND TWIST2 (CONT.)

STRESS IN ITEM ⑯ CONT.

FAILING STRAIN FOR ISSIE/EPOXY AT ±45°
IS

$\varepsilon \approx .03$ (SEE SKETCH, Pa. _4_)

$$M.S. = \frac{\varepsilon_{FAILURE}}{\varepsilon} -1 = \frac{.03}{.0171} -1 = \underline{\underline{+0.75}}$$

NONLINEAR THEORY IS REQUIRED,
THEREFORE SECTION PROPERTY CALCULATIONS
ARE MODIFIED BY REMOVING ITEMS ⑭
⑮ & ⑯ ($E = 0$ FOR THESE ITEMS WHEN
$\varepsilon > .0109$)

ITEM	AE	y	AEy	AEy²	EIo	
Σ	21.345	—	46.4931	187.6309	5.97027	
-⑭	-.691		-.00039	-.05511	-.00664	REF. Pa. _8_
-⑮	-3.208		-8.54744	-23.04113	-5.41081	
-⑯	-1.069		-5.47228	-28.03319	-.00935	
	16.377		32.21920	136.50866	.04207	

$$\bar{y} = \frac{\Sigma AEy}{\Sigma AE} = \frac{32.21920}{16.377} = 1.967$$

$$\Sigma EI_{NCO} = 2[136.50 + .04 - 1.967(32.219)]$$
$$= 146.3 \times 10^6$$

$$\Sigma AE_{NCO} = 2(16.377) = 32.75 \times 10^6$$

COMPOSITE HELICOPTER ROTOR HUB (CONT.)

(COND. TIV TYPE (CONT.)

LIMIT STRAIN FOR ITEM ⑯

$$\epsilon = \frac{F_{ty}}{E} = \frac{23,000}{2.2 \times 10^6} = .0109 \text{ in/in}$$

$$\epsilon = \frac{My}{EI} + \frac{P}{EAE} \qquad\qquad P = KM$$

$$K = \frac{P}{M} \text{ (ASSUMING P \& M INCREASE LINEARLY DURING LOADING)}$$

$$.0109 = \frac{M(3.08)}{183.7 \times 10^6} + \frac{.1137 \, M}{47.69 \times 10^6}$$

$$= (.01676 \times 10^{-6} + .00260 \times 10^{-6}) M \quad\} \quad = \frac{98426}{883756} = 0.11137$$

$$M = \frac{.0109 \times 10^6}{.01676 + .00260} \qquad\qquad y = 3.08 \, (\text{REF. P. } \underline{4})$$

$$= 563,000 \, \text{N}^\#$$

$$P = .1137 \, (563,000) = 67700^\#$$

$$\Delta M = M_{TOT} - M = 883756 - 563,000$$
$$= 320,756 \, \text{IN}^\#$$

$$\Delta P = P_{TOT} - P = 98424 - 67700$$
$$= 30724^\#$$

MJO NO. 3027-001	SUBJECT			DATE 10/5/71	CHECKED BY 13
TASK NO.				CALCULATIONS BY A.M.T.	SHEET NO. 11

COMPOSITE HELICOPTER ROTOR HUB (CONT.)

COND. TWTFL (CONT.)

STRESS IN ITEM ⑱

$$6 = \left(\frac{M_y}{\Sigma EI} + \frac{P}{\Sigma AE}\right) + \left(\frac{\Delta M_y}{\Sigma EI_{NW}} + \frac{\Delta P}{\Sigma AE_{NW}}\right), \quad Y = 3.20 \text{ (ref.)}$$

$$= \left[\frac{563,000(3.20)}{183.7 \times 10^6} + \frac{67700}{42.69 \times 10^6}\right]\left[\frac{320,134(3.00)}{146.3 \times 10^6} + \frac{30724}{30.75 \times 10^6}\right]$$

$$\Sigma EI = 183.7 \times 10^6$$
$$\Sigma AE = 42.69 \times 10^6$$
$$\Sigma EI_{NW} = 146.3 \times 10^6$$
$$\Sigma AE_{NW} = 30.75 \times 10^6$$

$$= .0139 + .00768$$

$$= .0191 \text{ in/in}$$

$$f_t = 6E$$
$$= .0191(3.9 \times 10^6)$$
$$= 74,500 \text{ psi (ct)}$$

$$E_{(P)} = .9 \times 10^6 \quad (\text{Ref. Pg. } 6)$$

$$F_{tu} = 84,000 \text{ psi (Ref. Pg. } 5)$$

$$M.S. = \frac{F_{tu}}{f_t} - 1, \quad \frac{84,000}{74,500} - 1 = \underline{\quad +0.13}$$

MJO NO	SUBJECT	DATE	CHECKED BY
8927-001		1/15/71	
TASK NO		CALCULATIONS BY	SHEET NO
		RNT	12

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COMPOSITE HELICOPTER ROTOR HUB (CONT.)

CONT. TWYFE2 (CONT.)

STRESS IN ITEM (1) (NONLINEAR THEORY)

$$\epsilon = \left(\frac{My}{\Sigma EI} + \frac{P}{\Sigma AE} \right) + \left(\frac{\Delta M}{\Sigma EI}_{NON} y + \frac{\Delta P}{\Sigma AE}_{NON} \right), \quad y = 3.31 \quad (\text{Ref. P. } 1)$$

$$= \left[\frac{563,000\,(3.31)}{183.7 \times 10^6} + \frac{67200}{42.69 \times 10^6} \right] + \left[\frac{320,756\,(3.31)}{146.3 \times 10^6} + \frac{30724}{32.75 \times 10^6} \right]$$

$$= .01173 + .00820$$

$$= .01993 \text{ in/in}$$

$$f_f = \epsilon E \qquad\qquad E = 5.3 \times 10^6 \, (\text{Ref. P. } 5)$$

$$= .01993\,(5.3 \times 10^6)$$

$$= 105,620 \text{ psi ULT.}$$

$$F_{tu} = 129,000 \text{ psi (Ref. P. } 5)$$

$$M.S. = \frac{F_{tu}}{f_f} - 1 = \frac{129,000}{105,620} - 1 = \underline{\underline{+0.22}}$$

MJO NO. 3027-001	SUBJECT			DATE 10/05/71	CHECKED BY
TASK NO				CALCULATIONS BY A.N.T.	SHEET NO. 13

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COMPOSITE HELICOPTER ROTOR HUB (CONT.)

CONT. TWIFZ (CONT.)

STRESS IN ITEM (13) (UPPER PLATE)

(NONLINEAR THEORY)

$$\epsilon = \left(\frac{M_{y_c}}{\Sigma EI} - \frac{P}{\Sigma EA}\right) + \left(\frac{\Delta M_{y_c}}{\Sigma_{mod} EI} - \frac{\Delta P}{\Sigma_{mod} AE}\right), \quad y_c = 2.30 \checkmark \quad \text{REF. 1B. } \underline{1}$$

$$= \left(\frac{563,000(2.30)}{183.7 \times 10^6} - \frac{67700}{42.6 \times 10^6}\right) + \left(\frac{320156(2.30)}{146.3 \times 10^6} - \frac{30724}{3275 \times 10^6}\right)$$

$$= .00546 + .00422$$

$$= .00968 \text{ in}^{-1}/\text{in}$$

$$f_c = \epsilon E \qquad\qquad E = 5.1 \times 10^6 \text{ psi}$$
$$= .00968 (5.1 \times 10^6) \qquad\quad (\text{REF. Pa. } 2)$$

$$= 49,360 \text{ psi ULT.}$$
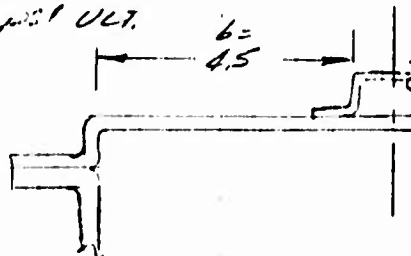
ALLOWABLE BUCKLING STRESS OF UPPER PLATE
(ITEM (13))

$$f_{cc} = \frac{\pi^2 k_c E}{12(1 - \mu^2)} \left(\frac{t}{b}\right)^2, \quad \text{REF. CROWN Pa. } C5.1 \,^{[14]}$$

MJO NO. 3027-001	SUBJECT		DATE 10/25/81	CHECKED BY
TASK NO.			CALCULATIONS BY A.M.T.	SHEET NO. 14

COMPOSITE HELICOPTER ROTOR HUB (CONT.)

COND. TW7F2 (CONT)

BUCKLING STRESS, ITEM ⑬ (CONT.)

$$\frac{b}{t} = \frac{2.5}{.124} = 20.1$$

$K_C = 5.2$, REF. BRUHN [14] FIG. C5.6

$$F_{CCR} = \frac{\pi^2 K_C E}{12(1-\mu^2)}\left(\frac{t}{b}\right)^2 \qquad E = 5.1 \times 10^6 \; (REF. R. 2)$$

$$= \frac{\pi^2 (5.2)(5.1 \times 10^6)}{12(1-.18)}\left(\frac{.124}{2.5}\right)^2 \qquad \mu \approx 0.18$$

$$= 55,800 \, psi$$

$$M.S. = \frac{F_{CCR}}{f_C} - 1 = \frac{55800}{49360} - 1 = \underline{\qquad +0.13}$$

COMPOSITE HELICOPTER ROTOR HUB (CONT.)

SECTION A-A

CONO. TW7F2

SHEAR STRESS

V = 54840 LBS ULT. (REF. PG. _9_)

ASSUME ENTIRE SHEAR CARRIED BY "BASKET,"
(ITEMS ⑭, ⑮ & ⑯)

⑯ N.A.

ITEM	A	E $\times 10^6$	AE $\times 10^6$	Y	AEY $\times 10^6$
1			.510	1.67	.852
2				1.35	.689
3				1.02	.520
4				.70	.357
5				.36	.184
6			.510	.02	.010
13			6.912	2.15	14.861
14			.691	1.89	1.306
15'	.567	2.2	1.247	.88	1.097

$$\Sigma = 19.876$$

$$\Sigma EQ = 2 (19.876 \times 10^6)$$

$$= 39.752 \times 10^6$$

MJO NO 3027-001	SUBJECT			DATE 11/3/71	CHECKED BY 15
TASK NO				CALCULATIONS BY A.M.T.	SHEET NO. 16

COMPOSITE HELICOPTER ROTOR HUB (CONT.)

SECTION A-A
CONN. TW7F2
SHEAR STRESS @ N.A. (CONT.)

$$f_s = \frac{V_N \Sigma EQ}{\Sigma EI \, b}$$

$$= \frac{59840 (39.752 \times 10^6)}{183.7 \times 10^6 (.648)}$$

$$= 18231 \, psi \; ULT.$$

$$\Sigma EI = 183.7 \times 10^6$$
$$(REF. \, P_h. \, \underline{8})$$
$$b = 2(.324)$$
$$= .648 \, IN$$

$$F_{su} = 24,000 (.9) = 21,600 \, psi \; @ \; 160°F$$
$$(15814/EPOXY \; @ \; ±45°)$$

$$M.S. = \frac{F_{su}}{f_s} -1 = \frac{21600}{18231} -1 = \underline{+0.18}$$

SHEAR ATTACHMENT ~ UPPER PLATE (ITEM 13)
TO BASKET (ITEM 14)

$$\Sigma EQ = 2(14.861 \times 10^6) = 29.72 \times 10^6 \; (REF. \, CALC. \, P_h. \, \underline{16})$$

$$q = \frac{V_N \Sigma EQ}{2 \; \Sigma EI}$$

$$= \frac{59840 (29.72 \times 10^6)}{2(183.7 \times 10^6)} = 4836 \, \#/IN \; ULT.$$

MJO NO 3027-001	SUBJECT		DATE 1/3/81	CHECKED BY
TASK NO			CALCULATIONS BY A.M.T.	SHEET NO 17

COMPOSITE HELICOPTER ROTOR HUB (CONT.)

SECTION A-A

COND. TIUTF2

SHEAR ATTACHMENT ~ UPPER PLATE TO BASKET

$$f_S = \frac{q}{w} = \frac{4436}{1.0} = 4436 \, psi \, ULT., \quad W = 1.0 \, IN. \, (BOND \, WIDTH)$$

$$F_S = 6500 \, psi \, (REF. \, WKR. \, TEST \, DATA)$$

$$M.S. = \frac{F_S}{f_S} - 1 = \frac{6500}{4436} - 1 = \underline{\quad\quad + 0.46}$$

SHEAR ATTACHMENT ~ LWR. PLATE TO BASKET

ITEM	AE	Y	AEY
17	1.473	3.20	4.714
18	1.872	3.16	5.916
		Σ	10.630

$$\Sigma EQ = 2(10.630) = 21,260 \times 10^6$$

$$q = \frac{V_N \, \Sigma EQ}{2 \, \Sigma EI}$$

$$= \frac{54840 (21,260 \times 10^6)}{2(183.7 \times 10^6)}$$

$$= 3173 \, \#/IN \, ULT. , \quad W = 1.15 \, IN \, (BOND \, WIDTH)$$

$$f_S = \frac{q}{w} = \frac{3173}{1.15} = 2759 \, psi \, ULT., \quad F_S = 6500 \, psi$$

$$M.S. = \frac{F_S}{f_S} - 1 = \frac{6500}{2759} - 1 = \underline{\quad\quad + 1.36}$$

COMPOSITE HELICOPTER ROTOR HUB (CONT.)

SECTION A-A
COND TIV7F2

SHEAR STRESS IN UPPER PLATE (ITEM ③)

@ EDGE OF BASKET
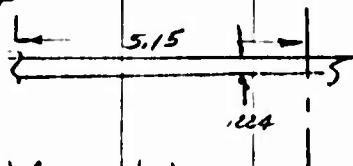
$$\Sigma Q = A y E$$

$$= 5.15 (.224)(2.15)(5.1 \times 10^6)(2)$$

$$= 25.3 \times 10^6$$

$$f_s = \frac{V_N \Sigma E Q}{\Sigma E I \, b}$$

$b = 2(.224)$

$= 0.448$

$\Sigma E I = 183.7 \times 10^6$ (REF NO. 1)

$$= \frac{54840 \left(25.3 \times 10^6\right)}{183.7 \times 10^6 (.448)}$$

$$= 16859 \, psi \, ULT.$$

$F_{su} = 21,600 \, psi$ @ 160°F
1591 & 0 ±45°

$$F_{su} = \frac{F_s \cdot t_{45} + F_s \cdot t_{0-90}}{t_{TOT}}$$

$$= \frac{21,600(.081) + 8200(.143)}{.224}$$

$F_{su} = 8200 \, psi$ @ 160°F
SCOTCHPLY'S @ 0-90
REF MIL HDBK 17 [3]
TABLE 4.30.

$$= 13,000 \, psi$$

M.S. ~ NEGATIVE ~ INCREASE TOP PLATE THICKNESS

MJO NO 3027-001	SUBJECT		DATE 11/12/71	CHECKED BY //5
TASK NO			CALCULATIONS BY A.M.T.	SHEET NO 19

COMPOSITE HELICOPTER ROTOR HUB (CONT.)

SECTION A-A
COND. TW7F2

SHEAR STRESS IN UPPER PLATE (ITEM ⑬) CONT.

INCREASE THICKNESS OF OUTB'D PORTION
OF TOP PLATE (ITEM ⑲)
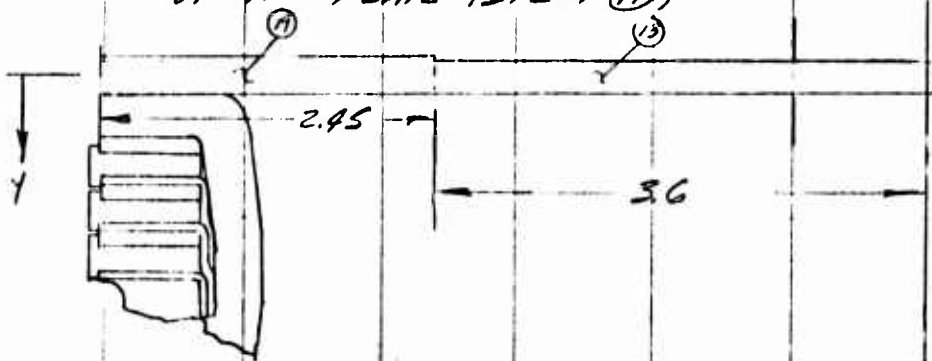
ITEM Ⓐ:

14 PLIES 1581 E $t = 14(.009) = .126$
19 PLIES SCOTCHPLY "S" $t = 19(.005) = .143$
$$t_{TOT} = .269$$

$$E = \frac{t_{1581} E_{1581} + t_{SCOTCH} E_{SCOTCH}}{t_{TOT}}$$

$$= \frac{.126(8.2 \times 10^6) + .143(6.8 \times 10^6)}{.269}$$

$$= 4.6 \times 10^6 \text{ psi}$$

M IO NO 3027-001	SUBJECT		DATE 11/4/71	CHECKED BY 17C
TASK NO			CALCULATIONS BY A.M.T.	SHEET NO 20

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COMPOSITE HELICOPTER ROTOR HUB (CONT.)

SECTION A-A

COND. TW7F2

REVISED SECTION PROPERTIES

REF. CALC. PG. __8__

ITEM	A	E	AE	y	AEy	AEy²	EIo
Σ			21.395	-	46.49031	187.62669	5.47027
-13			-6.912	-	-.16588	-.00398	-.02887
+13	3.6×.224=.806	5.1	4.113	.024	.09871	.00236	.01717
+19	2.05×.321=.659	4.6	3.031	.002	.00606	.00001	.01827
			21.577		46.42920	191.62488	5.47684

$$\bar{y} = \frac{\Sigma AEy}{\Sigma AE} = \frac{46.42920}{21.577} = 2.152$$

$$\Sigma EI = 2\left[\Sigma AEy^2 + \Sigma EI_o - \bar{y}\,\Sigma AEy\right]$$

$$= 2\left[187.62 + 5.48 - 2.152(46.929)\right]$$

$$= 166.4 \times 10^6 \, psi$$

@ OUTB'D EDGE OF ITEM ⑬

$$\Sigma EQ = 2\, A_{13} E_{13}\, y_{N.A.}$$

$$= 2\left[4.113\,(2.152 - .024)\right] \times 10^6$$

$$= 17.50 \times 10^6$$

MJO NO 3027-001	SUBJECT	DATE 11/52/71	CHECKED BY
TASK NO		CALCULATIONS BY A.M.T.	SHEET NO. 21

COMPOSITE HELICOPTER ROTOR HUB (CONT.)

SECTION A-A
COND. TW7F2
SHEAR STRESS IN ITEM ⑬

$$f_s = \frac{V \Sigma \varepsilon Q}{\Sigma \varepsilon I \, b}$$

$$= \frac{54890(12.50 \times 10^6)}{(186.4 \times 10^6)(.048)}$$

$$= 11,492 \text{ psi ULT.}$$

$\Sigma \varepsilon Q = 12.50 \times 10^6$

$\Sigma \varepsilon I = 186.4 \times 10^6$

$b = 2(.224)$
$\quad = 0.448$

$V = 54890$ LBS ULT.
$\quad$ (REF. PG. __9__)

FOR ITEM ⑬:

$$F_s = \frac{t_{1591} F_{s_{1591}} + t_{SCOTCH} F_{s_{SCOTCH}}}{t_{TOT}}$$

$$= \frac{.081(21,600) + .143(8200)}{.224}$$

$$= 13045 \text{ psi}$$

$$M.S. = \frac{F_{su}}{F_s} - 1$$

$$= \frac{13045}{11492} - 1 = \underline{\qquad \qquad +0.14}$$

COMPOSITE HELICOPTER ROTOR HUB (CONT.)

SECTION A-A
COND TW7F2
SHEAR STRESS IN ITEM ⑲ :

$$\Sigma EQ = 2\left[AE_{19}\,y_{19} + AE_{13}\,y_{13}\right], \quad \text{AT CORNER}$$

$$= 2\left[.030(6.6\times10^6)(2.150)\right.$$
$$\left. + 4.113\times10^6(2.128)\right]$$

$$= 26.0\times10^6$$

$$f_S = \frac{V_N\,\Sigma EQ}{\Sigma EI\,b}$$

$$= \frac{51840(26.0\times10^6)}{186.4\times10^6(.538)}$$

$$= 14,218 \text{ psi ULT.}$$

FOR ITEM ⑲ :

$$f_S = \frac{t_{581}\,F_{S_{1581}} + t_{SCOTCH}\,F_{S_{SCOTCH}}}{t_{TOT}}$$

$$= \frac{.126(31,600) + .143(8200)}{.269} = 14470 \text{ psi}$$

$$M.S. = \frac{F_S}{f_S} - 1 = \frac{14470}{14218} - 1 = \underline{\qquad\qquad} +.018$$

AT CORNER

$$A_{19}' = 1.6\times.269$$
$$= .430 \text{ in}^2$$

$$E_{19} = 1.6\times10^6$$
$$(REF. PG. \underline{20})$$

$$AE_{13} = 4.113\times10^6$$
$$(REF. PG. \underline{21})$$

$$y_{19} = 2.152 - .002$$
$$= 2.150$$

$$y_{13} = 2.152 - .024$$
$$= 2.128$$

$$b = 2(.269)$$
$$= .538$$

$$\Sigma EI = 186.4\times10^6$$
$$(REF. PG. \underline{21})$$

COMPOSITE HELICOPTER ROTOR HUB (CONT.)

SECTION A-A
CONU. TIU7F2

SHEAR STRESS IN LWR. PLATE (ITEM ⑬)
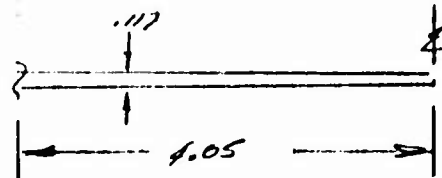
$\Sigma Q = 2 AE y$, $y = 5.34 - 2.152 = 3.19$

$= 2(.117)(4.05)(3.9 \times 10^6)(3.19)$

$= 11.79 \times 10^6$

$f_s = \dfrac{V_N \Sigma \Sigma Q}{\Sigma \Sigma I b}$

$b = 2(.117)$
$= .234$

$= \dfrac{54840 (11.79 \times 10^6)}{186.4 \times 10^6 (.234)}$

$= 14823 \, psi \; ULT.$

$F_S = \dfrac{t_{1581} F_{S_{1581}} + t_{SCOTCH} F_{S_{SCOTCH}}}{t_{TOT}}$

$= \dfrac{.072 (21,600) + .045 (8200)}{.117} = 16400 \, psi$

$M.S. = \dfrac{F_s}{f_s} - 1 = \dfrac{16400}{14823} - 1 = \underline{\underline{+0.11}}$

MJO NO 3027-001	SUBJECT			DATE 11/30/71	CHECKED BY 17 E
TASK NO				CALCULATIONS BY A. N.T.	SHEET NO. 24

COMPOSITE HELICOPTER ROTOR HUB (CONT.)

COND. TWJ7F1~SYM DIVE & PULLOUT
POWER ON

$$T_G = 99,000 \text{ LBS LIMIT}$$

$$V_G = 15,775 \text{ LBS LIMIT}$$

$$V_{N_{MAX}} = 34,300 \text{ LBS LIMIT}$$

$$M_G = 78,400 \text{ IN}^{\#} \text{ LIMIT}$$

$$M_N = 0$$

REF. STRESS
DOC. ___ SER. NO.
SEE ___ PG. 2

┌─────────────┐
│ SEE NOTE   │
│ PAGE 3   │
└─────────────┘

T_G ⟶
$= 99000^{\#} \text{LIMIT}$

$b = 12.90$

$V_N = 34,300^{\#} \text{LIMIT}$

$M_G = 78,400 \text{ IN}^{\#} \text{LIMIT}$
(VECTOR DIRECTION)

$\{ - R_B$
$\{ - R_A$

$- R_C$

$V_G = 15775^{\#} \text{LIMIT}$

PER POINT AXIAL LOAD:

$$T_{G_{TOT}} = T_G + \frac{M_G}{h} \quad , \quad h = \text{MOMENT ARM TO WRAPPER} = 9.812 \text{ IN}$$

$$= 99,000 + \frac{78400}{9.812} = 106,905 \text{ LBS LIMIT}$$

COMPOSITE HELICOPTER ROTOR HUB (CONT.)

COND. TW 7F1 (CONT.)

$$\left[T_{q_{TOT}}^2 + V_c^2\right]^{1/2} = \left[(106.905)^2 + (15775)^2\right]^{1/2}$$

$$= 108063 \; LBS \; LIMIT$$

$T_c + V_c = 108043$

$V_c = 15775$

$T_{c_{TO}} = 106905$
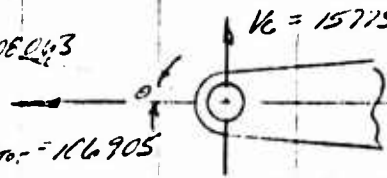
VIEW LKG. DN.

$$TAN \theta = \frac{15775}{106905} = 0.14756$$

$$\theta = 8°23.63'$$

[7]

FROM TIMKEN ENG. JOURNAL SECT. 2, PGS. 136 & 138 :

$$K_a = 1.24$$

$$K_b = 1.61$$

$$(R_A + R_B)\left(\frac{a+b}{2}\right) = (T_{q_{TOT}} + V_c)\,c$$

$$R_A + R_B = \frac{108063\,(5.237)\,(2)}{12.60 + 7.39} = 51944 \; LBS \quad LIMIT$$

$$\frac{0.47(R_A + R_B)}{K_a} = \frac{0.47(51944)}{1.24} = 19688$$

$$V_N = 34,300 > 19688, \therefore R_B = 0$$

MJO NO. 3027-001	SUBJECT		DATE 11/8/71	CHECKED BY
TASK NO			CALCULATIONS BY A.M.T.	SHEET NO. 26

100

COMPOSITE HELICOPTER ROTOR HUB (CONT.)

COND. TWJF1 (CONT.)

$$R_A = \frac{108063 \ (5.237)}{9.39} = 60269 \ LBS \ LIMIT$$

$$R_{A_{RADIAL}} = 60269 \ \cos \theta$$
$$= 60269 (.96929)$$
$$= 57624 \ LBS \ LIMIT$$

$$R_{A_{TRANSVERSE}} = 60269 \ \sin \theta$$
$$= 60269 (.14597)$$
$$= 8797 \ LBS. \ LIMIT$$

MJO NO 5027-001	SUBJECT				DATE 11/5/71	CHECKED BY
TASK NO					CALCULATIONS BY A.M.T.	SHEET NO 27

101

COMPOSITE HELICOPTER ROTOR HUB (CONT.)

SECTION A-A (SEE SKETCH, PG. ___1___)

SECTION PROPERTIES FOR SIDE SHEAR & BENDING.

ITEM	A	$E_{\times 10^6}$	$AE_{\times 10^6}$	X	$AEX_{\times 10^6}$	$AEX^2_{\times 10^6}$	$EI_0_{\times 10^6}$
1	.075	6.8	.510	5.67	2.89170	16.39593	.02390
2							
3							
4							
5							
6							
7							
8							
9							
10							
11							
12	.075	6.8	.510	5.67	2.89170	16.39593	.02390
13	1.355	5.1	6.912	3.03	20.94336	63.45938	1.08156
14	.314	2.2	.691	5.57	3.84887	21.43800	.05421
15	1.458	2.2	3.208	5.08	16.29664	80.78693	.02805
16	.486	2.2	1.069	4.38	4.68211	20.04351	.22096
17	1.278	5.3	1.473	4.72	6.95236	32.81608	1.19150
18	.450	3.9	1.872	2.05	3.83760	7.86708	2.62068
			21.345		111.20830	485.16040	7.04326

$$\sum_{1}^{71} EI = 2\left[\sum AEX^2 + \sum EI_0\right]$$

$$= 2\left[485.16 + 24.46\right] = 899.24 \times 10^6$$

COMPOSITE HELICOPTER ROTOR HUB (CONT.)

COND. TW 7F1
SECTION A-A

$59624 (1.5)$ ←
$= 89436$ LBS ULT.

$34300 (1.5)$
$= 51450$ LBS ULT.

13.1
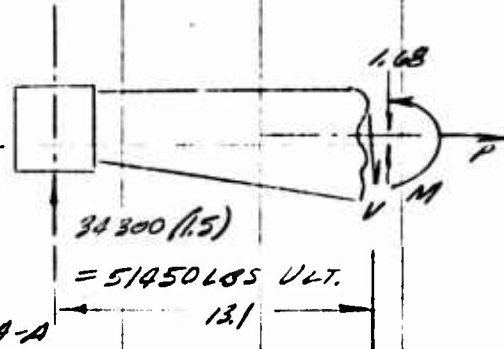
@ N.A. AT SECTION A-A

$M = 51450 (13.1) + 89436 (1.68)$

$= 824,247$ IN$^{\#}$ ULT.

$P = 89436$ LBS ULT.

$V = 51450$ LBS. ULT.

M JO NO. 3027-001	SUBJECT			DATE 11/8/71	CHECKED BY
TASK NO				CALCULATIONS BY A. N. T.	SHEET NO. 29

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COMPOSITE HELICOPTER ROTOR HUB (CONT.)

SECTION A-A
COND. TW7FI

VERTICAL BENDING & AXIAL LOAD ~

LIMIT STRAIN FOR ITEM (16)

$\epsilon = .0109 \, IN/IN, (REF. CALC. PG. \underline{11})$

$P = KM$

$\epsilon = \dfrac{MY}{\Sigma EI} + \dfrac{P}{\Sigma AE}, \qquad K = \dfrac{P}{M}$

$= \dfrac{89436}{824,247}$

$.0109 = \dfrac{M(3.08)}{183.7 \times 10^{6}} + \dfrac{0.1085 M}{42.69 \times 10^{6}} \qquad = 0.1085$

$.0109 = (.01676 \times 10^{-6} + .00254 \times 10^{-6})M \qquad Y_{n} = 3.08 \, IN \,(REF. PG. \underline{1})$

$\Sigma EI = 183.7 \times 10^{6} \,(REF. PG. \underline{1})$

$M = \dfrac{.0109}{.01930 \times 10^{-6}} \qquad \Sigma AE = 42.69 \times 10^{6} \,(\quad '' \quad)$

$= 564760 \, IN^{\#}$

$P = .1085 M$

$= .1085 (564760) = 61276^{\#}$

$\Delta M = M_{TOT} - M = 829,247 - 564760 = 259487 \, IN^{\#}$

$\Delta P = P_{TOT} - P = 89436 - 61276 = 28160^{\#}$

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COMPOSITE HELICOPTER ROTOR HUB (CONT.)

SECTION A-A
COND. TIII7FI

ABOVE LIMIT STRAIN FOR ITEM ___, ITEMS
(14), (15) & (16) ARE ASSUMED INEFFECTIVE

MODIFIED ΣEI & ΣAE ARE:

$$\Sigma EI_{NEW} = 196.3 \times 10^6, \text{ (REF. CALC. PG. ___)}$$

$$\Sigma AE_{NEW} = 32.75 \times 10^6, \text{ (REF. CALC. PG. ___)}$$

STRAIN IN (17):

$$\mathcal{E}_{17} = \left(\frac{My}{\Sigma EI} + \frac{P}{\Sigma AE}\right) + \left(\frac{\Delta My}{\Sigma EI_{NEW}} + \frac{\Delta P}{\Sigma AE_{NEW}}\right)$$

$$= \left[\frac{566760(3.31)}{183.7 \times 10^6} + \frac{612 K}{42.69 \times 10^6}\right]$$

$$+ \left[\frac{259087(3.31)}{196.3 \times 10^6} + \frac{8PK0}{32.75 \times 10^6}\right]$$

$\Sigma EI = 183.7 \ (REF. ___)$
$\Sigma AE = 42.69 \ (REF. ___)$
$y = 3.31 \text{ IN}$

$$= .0116/ + .00673$$

$$= .01834$$

$$f_{TENS} = \mathcal{E}_{17} E_{17}$$
$$= .01834(5.3 \times 10^6)$$
$$= 97,200 \, psi \ ULT.$$

$\mathcal{E}_{17} = 5.3 \times 10^6 \ (REF. PG. 5)$

MJO NO 3027-001	SUBJECT			DATE 12/1/71	CHECKED BY
TASK NO				CALCULATIONS BY A.M.T.	SHEET NO 31

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COMPOSITE HELICOPTER ROTOR HUB (CONT.)

SECTION A-A
COND. TW7F1

STRESS IN ITEM ⑭ DUE TO VERT. BENDING
& AXIAL LOAD:

$$\epsilon_{14} = \left(\frac{My}{\Sigma EI} - \frac{P}{\Sigma AE} \right) + \left(\frac{\Delta My}{\Sigma EI}_{M10} - \frac{\Delta P}{\Sigma AE}_{M10} \right), \quad Y_{14} = 2.07$$

$$= \left(\frac{564760(2.07)}{183.7 \times 10^6} - \frac{61216}{42.69 \times 10^6} \right) + \left(\frac{259487(2.07)}{143.6 \times 10^6} - \frac{28160}{32.75 \times 10^6} \right)$$

$$= .00493 + .00288$$

$$= .00781$$

$$f_{c_{14}} = \epsilon_{14} E_{14} \qquad\qquad E_{14} = 2.2 \times 10^6$$
$$\qquad\qquad\qquad\qquad (15.1(0) \pm 45°)$$

$$= .0078/(2.2 \times 10^6)$$

$$= 17,180 psi ULT. \text{ (SEE PAGE 34 FOR COMBINED}$$
$$\text{COMPRESSION STRESS)}$$

MJO NO 3027-001	SUBJECT			DATE 12/1/71	CHECKED BY 70E
TASK NO				CALCULATIONS BY A.M.T.	SHEET NO. 32

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COMPOSITE HELICOPTER ROTOR HUB (CONT.)

SECTION A-A
COND. TWTF1

SIDE BENDING ~

$V_{A_{TRANS.}} = 8797(1.5) = R_{A_{TRANS.}}$
$= 13196^{\#} ULT$
(REF. PG. 27)

$M_{SIDE} = V_A \ell$
$= 13196(13.1) = 172,868 \, IN^{\#} ULT.$

STRESS IN ITEM ⑰ DUE TO SIDE BENDING ~

$f_{b_{SIDE_{17}}} = \dfrac{M \times E}{\Sigma EI_{YY}}$,
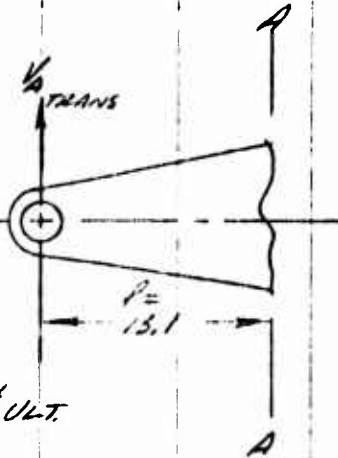
$= \dfrac{172868(5.35)(5.3 \times 10^6)}{899.24 \times 10^6}$

$= 5451 \, psi \, TOT$

$x_{17} = 5.35$
$\Sigma EI_{YY} = 899.24 \times 10^6$
(REF. PG. 28)
$E_{17} = 5.3 \times 10^6$
(REF. PG. 5)

$f_{t_{TOT}} = f_{t_{NET}} + f_{t_{SIDE}}$,
$= 97,200 + 5451$
$= 102651 \, psi \, ULT.$

$f_{t_{NET}} = 97,200 \, psi \, ULT.$
(REF. PG. 31)

$F_{tu_{17}} = 129,000 \, psi \, (REF. PG. 5)$

$M.S. = \dfrac{F_{tu}}{f_t} - 1 = \dfrac{129,000}{97,200} - 1 = \underline{\hspace{2cm} + 0.33}$

COMPOSITE HELICOPTER ROTOR HUB (CONT.)

SECTION A-A
COND. TW7F1

STRESS IN ITEM ⑭ DUE TO SIDE BENDING ~

$$f_{b_{c_{SIDE_{14}}}} = \frac{M \times E}{\Sigma E I_{y-y}}$$

$$\bar{x}_{14} = 6.05 \text{ IN}$$

$$\Sigma E I_{y-y} = 899.24 \times 10^6$$
(REF. PG. 26)

$$= \frac{172868 (6.05)(2.2 \times 10^6)}{899.24 \times 10^6}$$

$$E_{14} = 2.2 \times 10^6$$

$$= 2559 \text{ PSI ULT.}$$

$$f_{c_{TOT_{14}}} = f_{c_V} + f_{c_{SIDE}} \quad , \quad f_{c_V} = 17180 \text{ PSI ULT.}$$
(REF. PG. 32)

$$= 17180 + 2559$$

$$= 19739 \text{ PSI ULT.}$$

$$F_{tu_{181 @ 45°}} = 24,000 \text{ PSI (REF. PG. 5)}$$

ASSUME $F_c = F_{tu}$

$$M.S. = \frac{F_c}{f_c} - 1$$

$$= \frac{24,000}{19739} - 1 = \underline{\hspace{3cm}} \quad +0.22$$

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COMPOSITE HELICOPTER ROTOR HUB (CONT.)

SECTION A-A
CONC TW7F1

SHEAR IN BONDED ATTACHMENT OF
UPPER PLATE TO BASKET (ITEM ④ TO
ITEM ⑭) - SEE SKETCH, PG. 20

FROM VERT. SHEAR:

$$q_V = \frac{V_N \Sigma EQ}{2 \Sigma EI} ,$$

$$= \frac{51540 (26.0) \times 10^6}{2 (186.4 \times 10^6)}$$

$$= 3595 \; ^{\#}/_{IN} \; ULT.$$

$V_N = 34300(1.5)$
$= 51540^{\#} ULT.$
$(REF. PG. \underline{25})$

$\Sigma EQ = 26.0 \times 10^6$
$(REF. PG. \underline{23})$

$\Sigma EI = 186.4 \times 10^6$
$(REF. PG. \underline{21})$

FROM SIDE SHEAR:

ASSUME SHEAR STRAIN IN UPPER PLATE ⑬
EQUALS SHEAR STRAIN IN LWR. PLATE ⑭

$$\gamma_{⑬} = \gamma_{⑭}$$

$$f_S = \gamma G , \quad q = f_S t$$

$$q_{⑬} = f_{S_{⑬}} t_{⑬} = \gamma_{⑬} G_{⑬} t_{⑬}$$

$$q_{⑭} = \gamma_{⑭} G_{⑭} t_{⑭}$$

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COMPOSITE HELICOPTER ROTOR HUB (CONT.)

SECTION A-A

COND. TW7F1

$$\left(q_{(3)} + q_{(18)}\right) w = V_{A_{TRANS.}}$$

$$\gamma_{(13)} \left(G_{18} t_{(18)} + G_{13} t_{(13)}\right) w = V_{A_{TRANS.}}$$

$$\gamma_{(13)} = \frac{V_{A_{TRANS.}}}{\left(G_{18} t_{18} + G_{13} t_{13}\right) w}$$

$$= \frac{13196}{\left[\left(1.09 \times 10^6\right)(.117) + .89 \times 10^6(.224)\right] 10.0}$$

$$= 4037 \times 10^{-6}$$

$$q_{(13)_s} = \gamma_{13} G_{13} t_{(13)}$$

$$= 4037 \times 10^{-6}(.89 \times 10^6)(.224)$$

$$= 805 \text{ #/}_{IN} \text{ ULT.}$$

$$q_{(18)_s} = \gamma_{(13)} G_{18} t_{(18)}$$

$$= 4037 \times 10^{-6}(1.09 \times 10^6)(.117)$$

$$= 515 \text{ #/}_{IN} \text{ ULT.}$$

$$w = WIDTH = 10_{IN}$$

$$V_{A_{TRANS.}} = 13196^{\#} \text{ ULT.}$$

(REF. P. 33.)

$$G_{18} = \frac{t_{1581} G_{1581} + t_{SCOTCH} G_{SCOTCH}}{t_{TOT}}$$

$$= \frac{.072(1.4 \times 10^6) + .045(0.6 \times 10^6)}{.117}$$

$$= 1.09 \times 10^6$$

$$G_{13} = \frac{.091(1.4 \times 10^6) + .133(.6 \times 10^6)}{.224}$$

$$= 0.89 \times 10^6$$

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COMPOSITE HELICOPTER ROTOR HUB (CONT.)

SECTION A-A

COND. TWTF1

SHEAR CTR. :

$V = 8050^\# ULT.$

SHEAR CTR.

$\bar{y} = 3.24$

1.77

5.31

$5150^\# ULT.$

IN UPPER PLATE,
ITEM ⑬

$$V = \frac{q}{13} \omega$$

$$= 805 (10) = 8050 ^\# ULT.$$

IN LOWER PLATE,
ITEM ⑬

$$V = \frac{q}{15} \omega$$

$$= 515 (10) = 5150 ^\# ULT.$$

FROM ΣM AT BOTTOM PLATE

$$V_{A_{TRANS.}} \bar{y} = 8050 (5.31)$$

$$\bar{y} = \frac{8050 (5.31)}{13196} = 3.24 IN$$

SIDE LOAD IS APPLIED 1.77 IN BELOW THIS PT.

$$T = V_{A_{TRANS.}} (1.77)$$

$$= 13196 (1.77) = 23357 IN^\# ULT.$$
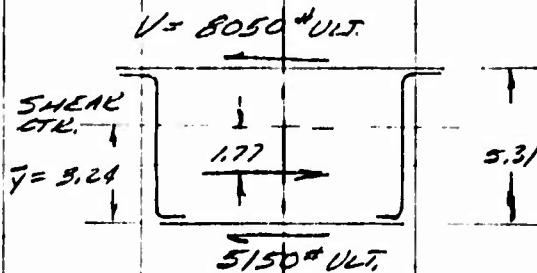
M JO NO 9027-001	SUBJECT			DATE 12/3/71	CHECKED BY zn J
TASK NO				CALCULATIONS BY A.N.T.	SHEET NO. 37

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COMPOSITE HELICOPTER ROTOR HUB (CONT.)

SECTION A-A
COND. TW7F1

SHEAR FLOW DUE TO TORQUE

$$q_T = \frac{T}{2A}$$

$$= \frac{23257}{2(53.53)}$$

$$= 218 \ \#/\text{IN} \ U.T.$$

$A = 5.3 \times 10.1$
$\quad = 53.53$

@ UPPER CORNER (PT. A)

$$q = q_V + q_S - q_T$$

$$= 3595 + 805 - 218$$

$$= 4182 \ \#/\text{IN} \ U.T.$$

$$f_{s_{(19)}} = \frac{q}{t}$$

$$= \frac{4182}{.269} = 15546 \ \text{psi} \ U.T.$$

FOR ITEM (19)

$t = 0.269 \ (\text{REF. P. } 20)$

$$F_S = 14470 \ \text{psi} \ U.T. \ (\text{REF. P. } 23)$$

$$M.S. = \frac{F_S}{f_{s_{(19)}}} - 1$$

$$= \frac{14470}{15546} - 1 = \quad\quad\quad\quad -.069$$

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COMPOSITE HELICOPTER ROTOR HUB (CONT.)

SECTION A-A
COND. TW7F1

SHEAR STRESS IN ITEM ⑲ IS TOO HIGH, ∴
INCREASE THICKNESS OF ITEM ⑦ BY
2 PLIES 1581E @ ±45°

LAYUP IS:
16 PLIES 1581E , $t = 16(.009) = .144$
19 PLIES SCOTCHPLY 5 , $t = 19(.0075) = \underline{.143}$

$$t_{TOT} = .287$$

$$F_S = \frac{t_{1581} \, F_{S_{1581}} + t_{scotch} \, F_{S_{scotch}}}{t_{TOT}}$$

$$= \frac{.144 (21,600) + .143 (8200)}{.287}$$

$$= 14920 \, psi$$

$$f_{S_{\textcircled{7}}} = \frac{q}{t} = \frac{4182}{.287} = 14571 \, psi \, ULT.$$

$$M.S. = \frac{F_S}{f_{S_{\textcircled{7}}}} - 1$$

$$= \frac{14920}{14571} - 1 = \quad\quad\quad\quad +.024$$

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TASK NO			CALCULATIONS BY L. M. T.	SHEET NO 39

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COMPOSITE HELICOPTER ROTOR HUB (CONT.)

SECTION A-A

COND TWYFI

SHEAR STRESS IN CONDLO ATTACHMENT
AT UPPER CORNER (ITEM ⑰ TO ITEM ⑭)

$$f_s = \frac{q}{w},$$

$$= \frac{4182}{1.0}$$

$$= 4182 \text{ psi}$$

$w = $ BOND WIDTH

$\quad = 1.0$ IN

$q = 4182 \text{ }^{\#}/_{IN} \text{ ULT.}$

$\quad$ (REF. PG. $\underline{38}$)

$$F_{su} = 6500 \text{ psi (REF. WKR TEST DATA)}$$

$$M.S. = \frac{F_s}{f_s} - 1$$

$$= \frac{6500}{4182} - 1 = \text{_____ } +0.55$$

COMPOSITE HELICOPTER ROTOR HUB (CONT.)

SECTION B-B (19.9 IN OUTB'D OF HUB ℄)

NOTE~ TOP PLATE THICKNESS INCREASED
TO 0.156 IN (SEE Pg. 50 & 58)
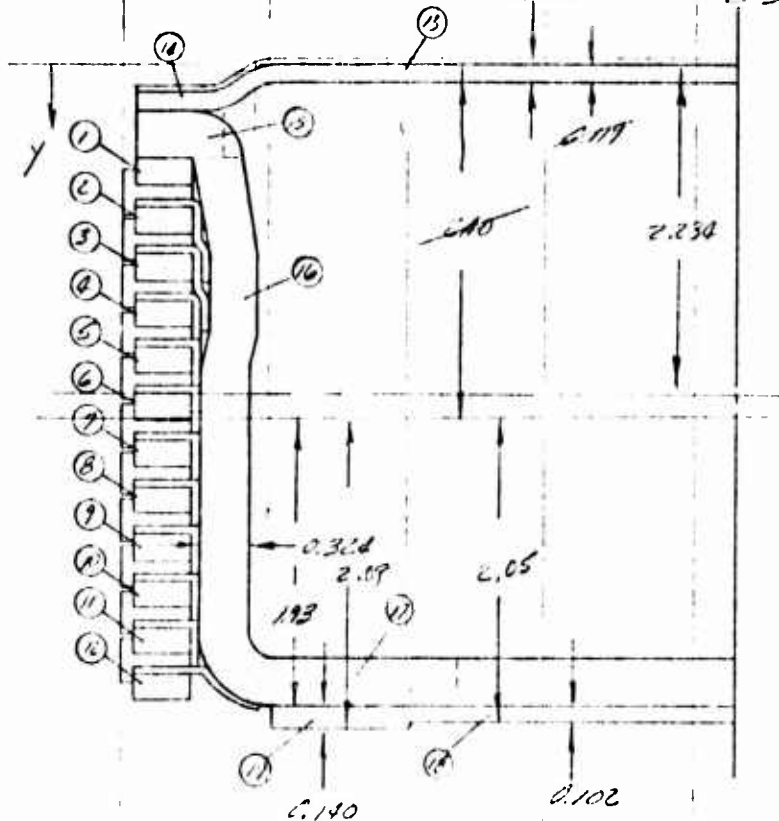
MJO NO	SUBJECT	DATE	CHECKED BY
3027-001		10/26/71	
TASK NO		CALCULATIONS BY A.A.T.	SHEET NO 41

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COMPOSITE HELICOPTER ROTOR HUB (CONT.)

SECTION B-B (CONT.)

ITEMS ① THROUGH ⑫, FILAMENT-WOUND
"S" GLASS, $E = 6.8 \times 10^6$
$F_{TU} = 180,000 \, psi$

ITEM ⑬ & ⑭

5 PLIES SCOTHPLY "S", $t = 5(.0075) = .038$

9 PLIES 1581E @ ±45°, $t = 9(.009) = \underline{.081}$

$$t_{TOT} = .119$$

$$E = \frac{.038(6.8 \times 10^6) + .081(2.2 \times 10^6)}{.119}$$

$$= 3.7 \times 10^6$$

$$F_{TU} = \frac{.038(180,000) + .081(24,000)}{.119}$$

$$= 73,800 \, psi$$

ITEMS ⑮ ⑯ & ⑰

36 PLIES 1581E @ ±45°, $t = 36(.009) = .324$

$$E = 2.2 \times 10^6 \, psi$$

$$F_{TU} = 24,000 \, psi$$

ITEM ⑱

4 PLIES SCOTCHPLY "S", $t = 4(.0075) = .030$

8 PLIES 1581E @ ±45°, $t = 8(.009) = \underline{.072}$

$$t_{TOT} = 0.102$$

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COMPOSITE HELICOPTER ROTOR HUB (CONT.)

SECTION B-B

ITEM (18) CONT.

$$E = \frac{.030(6.8 \times 10^6) + .072(2.2 \times 10^6)}{0.102}$$

$$= 3.5 \times 10^6$$

$$F_t = \frac{.030(180,000) + .072(24,000)}{.102}$$

$$= 69,800 \, psi$$

ITEM (19)

9 PLIES SCOTCHPLY "S", $t = 9(.0075) = .068$

8 PLIES 181E @ ±45°, $t = 8(.009) = .072$

$t_{TOT} = 0.140$

$$E = \frac{.068(6.8 \times 10^6) + .072(2.2 \times 10^6)}{.140}$$

$$= 4.4 \times 10^6$$

$$F_{tu} = \frac{.068(180,000) + .072(24,000)}{.140}$$

$$= 99770 \, psi$$

MJO NO. 3027-001	SUBJECT		DATE 10/27/71	CHECKED BY ᴢ3
TASK NO			CALCULATIONS BY A.M.T.	SHEET NO. 43

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COMPOSITE HELICOPTER ROTOR HUB (CONT.)

SECTION PROPERTIES ~ SECTION B-B

ITEM	A	E $\times 10^6$	AE $\times 10^6$	y	AEy $\times 10^6$	AEy² $\times 10^6$	EI₀ $\times 10^6$
1 . 4×.185=.075	6.8	510	0.73	.37230	.27177	.00150
2			1.06	.54060	.57303	
3			1.38	.70380	.97124	
4			1.70	.86700	1.47390	
5			2.01	1.02510	2.06045	
6			2.33	1.18830	2.76513	
7			2.64	1.34640	3.55449	
8			2.96	1.50960	4.46841	
9			3.28	1.67280	5.48678	
10			3.58	1.82580	6.53636	
11			3.92	1.99920	7.83686	
12	.075	6.8	.510	4.22	2.15220	9.08228	.00150
13 ..×.. .405	3.7	1.499	.06	.08994	.00539	.00176
14 .... .095	3.7	.352	.26	.09152	.02379	.0009!
15 .. ×.. .188	2.2	.414	.48	.19872	.09538	.00361
16 ... 1.095	2.2	2.409	2.32	5.58888	12.96620	2.29369
17 ... .486	2.2	1.069	4.16	4.96842	18.67799	.00935
18 7.28×... .233	3.5	.816	4.40	3.59040	15.79776	.00076
19 ...×.. .140	4.4	.616	4.42	2.72272	12.03442	.00100
	3.542		13.295		31.95370	104.68523	2.32650

$$\bar{y} = \frac{\Sigma AEy}{\Sigma AE} = \frac{31.95370}{13.295} = 2.403$$

$$\Sigma AE = 2(13.295)$$
$$= 26.59 \times 10^6$$

$$\Sigma EI = 2[\Sigma AEy^2 + \Sigma EI_0 - \bar{y}\Sigma AEy]$$
$$= 2[104.69 + 2.33 - 2.403(31.954)] = 60.5 \times 10^6$$

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COMPOSITE HELICOPTER ROTOR HUB (CONT.)

COND. TWIFZ

$R_A = 98424^\# ULT.$

SEE NOTE
PAGE 3

$V_N = 54840^\# ULT.$
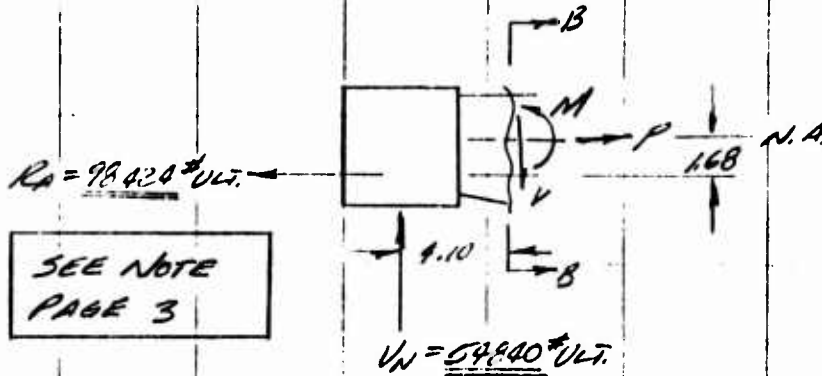
AT N.A. AT SECTION B-B

$M = 54840 (4.10) + 98424 (1.68)$

$= 390196 \ IN^\# ULT.$

$P = 98424 \ LBS. \ ULT.$

$V = 54840 \ LBS \ ULT.$

NONLINEAR THEORY IS USED;

STRAIN IN ITEM ①

$\epsilon = \dfrac{My}{\Sigma EI} + \dfrac{P}{\Sigma AL}$, $\quad y = 1.95$

$= \dfrac{390196(1.95)}{60.5 \times 10^6} + \dfrac{98424}{26.59 \times 10^6} = .0163$

STRAIN @ FAILURE, $\epsilon_{max} \approx .03$

$M.S. = \dfrac{\epsilon_{max}}{\epsilon} - 1 = \dfrac{.03}{.0163} - 1 = \text{———} + 0.84$

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COMPOSITE HELICOPTER ROTOR HUB (CONT.)

SECTION B-B
COND. TW7F2 (CONT.)

STRAIN @ YIELD FOR ITEM (17)

$$\epsilon = \frac{F}{E} = \frac{24,000}{2.2 \times 10^6} = .0109 \ IN/IN$$

ABOVE THIS STRAIN LEVEL, E FOR ITEMS
(15) (16) & (17) IS ASSUMED TO BE 0.

MODIFIED SECTION PROPERTIES:

ITEM	AE	AEy	AEy²	EI₀
5	13.295	31.95370	109.69523	2.32852
-15	-.414	-.19872	-.09538	-.00361
-16	-2.409	-5.58888	-12.96620	-2.29369
-17	-1.069	-4.46892	-18.67799	-.00935
	9.403	21.69768	77.94566	.02187

$$\bar{y} = \frac{\Sigma AEy}{\Sigma AE} = \frac{21.69768}{9.403} = 2.308$$

$$\underset{MOD}{\Sigma EI} = 2 \left[\Sigma AEy^2 + \Sigma I_0 - \bar{y} \Sigma AE \right]$$

$$= 2 \left[77.95 + .02 - 2.308 (21.698) \right]$$

$$= 45.8 \times 10^6$$

$$\underset{MOD}{\Sigma AE} = 2 \left[9.403 \right] = 18.806 \times 10^6$$

MJO NO 3027-001	SUBJECT	DATE 10/26/71	CHECKED BY
TASK NO		CALCULATIONS BY A.N.T.	SHEET NO. 46

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COMPOSITE HELICOPTER ROTOR HUB (CONT.)

SECTION B-B

CONV TWIFR (CONT.)

LIMIT STRAIN FOR ITEM (17)

$$\epsilon = .0109 = \frac{My}{\Sigma EI} + \frac{P}{\Sigma AE}$$

$$P = KM$$

$$K = \frac{P}{M} = \frac{98424}{390196}$$

$$= .25224$$

$$.0109 = \frac{M(1.93)}{60.5 \times 10^6} + \frac{.25224 M}{26.59 \times 10^6}$$

$$Y_{17} = 1.93 \ (\text{REF. Pk. } 41)$$

$$M = \frac{.0109}{.04136 \times 10^{-6}}$$

$$\Sigma EI = 60.5 \times 10^6$$
$$(\text{REF. Pk. } 44)$$

$$= 263410 \ IN^{\#}$$

$$\Sigma AE = 26.59 \times 10^6$$
$$(\text{REF. Pk. } 44)$$

$$P = .25224 (263410)$$

$$\underset{MOD}{\Sigma} EI = 45.8 \times 10^6$$
$$(\text{REF. Pk. } 46)$$

$$= 66443 \ LBS.$$

$$\Delta M = M_{TOT} - M$$

$$\underset{MOD}{\Sigma} AE = 18.806 \times 10^6$$
$$(\text{REF. Pk. } 46)$$

$$= 390196 - 263410 = 126,786 \ IN^{\#}$$

$$\Delta P = P_{TOT} - P$$

$$= 98424 - 66443 = 31981^{\#}$$

STRAIN IN ITEM (18)

$$\epsilon = \left(\frac{My}{\Sigma EI} + \frac{P}{\Sigma EA} \right) + \left(\frac{\Delta My}{\underset{MOD}{\Sigma} EI} + \frac{\Delta P}{\underset{MOD}{\Sigma} AE} \right) , \ Y_{18} = 2.05 \ (\text{REF. Pk. } 31)$$

$$= \left(\frac{263410 (2.05)}{60.5 \times 10^6} , \frac{66443}{26.59 \times 10^6} \right) + \left(\frac{126786 \times 2.05}{45.8 \times 10^6} + \frac{31981}{18.806 \times 10^6} \right)$$

$$= .01141 + .00737 = .0188 \ IN/IN @ ULT.$$

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TASK NO				CALCULATIONS BY A.M.T.	SHEET NO. 47

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COMPOSITE HELICOPTER ROTOR HUB (CONT.)

SECTION B-B
COND TW7F2 (CONT.)
STRESS IN ITEM (18) CONT.

$$f_t = \epsilon E \qquad\qquad E = 3.5 \times 10^6 \ (\text{REF. PG. } 43)$$

$$= .0108 \ (3.5 \times 10^6)$$

$$= 65,730 \ psi$$

$$F_{TU} = 69,800 \ psi \ (\text{REF. PG. } 43)$$

$$M.S. = \frac{F_{TU}}{f_t} - 1 = \frac{69,800}{65,730} - 1 = \quad\quad\quad +0.06$$

STRAIN IN ITEM (19)

$$\epsilon = \left(\frac{My}{\Sigma EI} + \frac{P}{\Sigma AE} \right) + \left(\frac{\Delta My}{\Sigma_{MOD} EI} + \frac{\Delta P}{\Sigma_{MOD} AE} \right), \ y = 2.09 \ (\text{REF. PG. } 41)$$

$$= \left[\frac{263410 \ (2.09)}{60.5 \times 10^6} + \frac{66413}{26.59 \times 10^6} \right] + \left[\frac{126786 \ (2.09)}{45.8 \times 10^6} + \frac{31781}{18.86 \times 10^6} \right]$$

$$= .0116 + .0075$$

$$= .0191$$

$$f_t = \epsilon E \qquad\qquad E_A = 4.4 \times 10^6 \ (\text{REF. PG. } 43)$$

$$= .0191 \ (4.4 \times 10^6)$$

$$= 84040 \ psi \ ULT.$$

$$F_{TU} = 99770 \ psi \ (\text{REF. PG. } 43)$$

$$M.S. = \frac{F_{TU}}{f_t} - 1 = \frac{99770}{84040} - 1 = \quad\quad\quad +0.19$$

MJO NO 3027-001	SUBJECT	DATE 10/27/71	CHECKED BY ZS
TASK NO		CALCULATIONS BY A. M. T.	SHEET NO. 48

COMPOSITE HELICOPTER ROTOR HUB (CONT.)

SECTION B-B
COND. TU7F2

STRAIN IN ITEM ⑬

$$E = \left(\frac{My}{\Sigma EI} - \frac{P}{\Sigma AE} \right) + \left(\frac{\Delta My}{\underset{MND}{\Sigma} EI} + \frac{\Delta P}{\underset{MND}{\Sigma} AE} \right), \quad y = 2.40$$

(REF. Pa. 41)

$$= \left[\frac{263410 (2.40)}{60.5 \times 10^6} - \frac{66443}{2659 \times 10^6} \right] + \left[\frac{126786 (2.40)}{45.8 \times 10^6} - \frac{31981}{12.806 \times 10^6} \right]$$

$$= .00795 + .00494$$

$$= .01289 \text{ IN/IN} \quad @ \text{ ULT.}$$

$$f_c = EE$$
$$= .01289 (3.7 \times 10^6)$$
$$= 47,700 \text{ PSI ULT.}$$

$$E = 3.7 \times 10^6$$
(REF. Pa. 42)

BUCKLING ALLOWABLE
STRESS FOR ITEM ⑬

$$\frac{b}{f} = \frac{3.0}{.119} = 25.2$$

$$k_c = 5.4 \text{ (REF. BRUHN, FIG. C5.6)}^{[14]}$$

$$F_{cr} = \frac{\pi^2 k_c E}{12(1 - \mu^2)} \left(\frac{f}{b} \right)^2$$
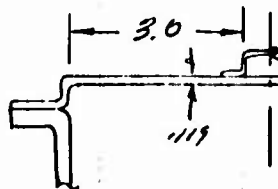
$$= \frac{\pi^2 (5.4)(3.7 \times 10^6)}{12(1 - .15)} \left(\frac{.119}{3.0} \right)^2 = 26,700 \text{ PSI}$$

MJO NO	SUBJECT	DATE	CHECKED BY
3027-001		10/27/71	27
TASK NO		CALCULATIONS BY	SHEET NO.
		A. M. T.	49

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COMPOSITE HELICOPTER ROTOR HUB (CONT.)

SECTION B-B

COND. 7W7F2 (CONT.)

M.S. ~ NEGATIVE FOR ITEM ⑬

∴ INCREASE UPPER PLATE THICKNESS

FOR ITEM ⑬ & ⑭ ~

10 PLIES SCOTCHPLY "S", $t = 10(.0075) = .075$

9 PLIES 1581 E ⊕ ±45°, $t = 9(.009) = .081$

$$t_{TOT} = 0.156$$

$$E = \frac{.075(6.8 \times 10^6) + .081(2.2 \times 10^6)}{0.156}$$

$$= 4.4 \times 10^6$$

$$F_{tu} = \frac{.075(180,000) + .081(24,000)}{.156}$$

$$= 99,000 \, psi$$

REVISED SECTION PROPERTIES:

ITEM	A	E	AE	$\bar{y}$	$AE\bar{y}$	$AE\bar{y}^2$	EI_0
Σ REF Pt. 14			13.295	—	31.95370	104.68523	2.32852
-13			-1.499	—	-.05994	-.00539	-.00176
-14			-.352	—	-.09152	-.02379	-.00041
+13 3.4×.156=.530		4.4	2.332	.041	.09561	.00392	.00472
+14 .156·E=.125		4.4	.550	.24	.13200	.03168	.00111
			14.326		31.99985	104.69165	2.33218

$$\bar{Y} = \frac{\Sigma AE\bar{y}}{\Sigma AE} = \frac{31.99985}{14.326} = 2.234 \,, \quad \Sigma AE = 2(A.320)$$
$$= 28.652 \times 10^6$$

$$\Sigma EI = 2 \left[104.69 + 2.33 + 2.234(32.00) \right] = 71.06 \times 10^6$$

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COMPOSITE HELICOPTER ROTOR HUB (CONT.)

SECTION B-B

COND. TW7F2 (CONT.)

ALLOWABLE BUCKLING STRESS OF UPPER
PLATE:

$$\frac{b}{t} = \frac{3.0}{.156} = 19.23$$

$$k_c = 5.2 \ (REF.\ BRUHN,\ ^{[14]}\ FIG.\ C5.6)$$

$$F_{cr} = \frac{\pi^2 k_c E}{12(1-\mu^2)} \left(\frac{t}{b}\right)^2$$

$$= \frac{\pi^2 (5.2)(9.4 \times 10^6)}{12(1-.18^2)} \left(\frac{.156}{3.0}\right)^2$$

$$= 52,500\ psi$$

WITH REVISED X-SECTION

$$f_c < 47,700\ psi\ (REF\ CALC.\ N_o.\ \underline{44})$$

$$M.S. > \frac{F_{cr}}{f_c} - 1$$

$$> \frac{52,500}{47,700} - 1 = \underline{\quad - \quad} > +0.10$$

NJO NO.		SUBJECT			DATE 11/16/71	CHECKED BY 3'
TASK NO					CALCULATIONS BY A.M.T.	SHEET NO. 51

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COMPOSITE HELICOPTER ROTOR HUB (CONT.)

SECTION 15-B

COND. JW7F2

SHEAR STRESS ~

V = 59840 LBS ULT.

ASSUME ENTIRE SHEAR CARRIED BY "BASKET" (ITEMS ⑤, ⑯ & ⑬)

@ N.A.

ITEM	A	E ×10⁶	AE ×10⁶	Y	AEY ×10⁶
1	.075	6.8	.510	1.49	.760
2				1.16	.592
3				.85	.434
4				.54	.275
5	.075	6.8	.510	.22	.112
13	.530	4.4	2.332	2.19	5.107
14	.125	4.4	.550	2.00	1.100
15	.188	2.2	.414	1.75	.725
16	.525	2.2	1.155	.81	.936
					10.041

$$\Sigma EQ_{NA} = 2(10.041) \times 10^6$$

$$= 20.082 \times 10^6$$

MJO NO	SUBJECT			DATE 11/16/71	CHECKED BY
3027-001					
TASK NO				CALCULATIONS BY A.M.T.	SHEET NO. 52

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COMPOSITE HELICOPTER ROTOR HUB (CONT.)

SECTION B-B
COND. TW.7F?
SHEAR STRESS (CONT.)

$$f_s = \frac{V_N \Sigma EQ}{\Sigma EI \, b}$$

$$= \frac{54840(20.82 \times 10^6)}{71.06 \times 10^9 (.648)}$$

$$= 24,795 \, psi$$

M.S. ~ NEGATIVE

ADD 2.5 WIDE DOUBLER
TO INNER SURFACE OF (16)

$$t = 8(.009) = .072$$

CHANGE IN ΣEQ & ΣEI IS NEGLIGIBLE

$$f_s = \frac{V \Sigma EQ}{\Sigma EI \, L}$$

$$= \frac{54840(20.82 \times 10^6)}{71.06 \times 10^9 (.792)}$$

$$= 20287 \, psi \, ULT.$$

$$M.S. = \frac{F_{su}}{f_s} -1 = \frac{21600}{2.02.87} -1 = \underline{\quad +.06}$$

$V_N = 54840^\# ULT.$
REF. PG. 9

$\Sigma EI = 71.06 \times 10^6$
REF. PG. 50

$b = 2(.324)$
$= .648 IN$

$\Sigma EQ = 20.082 \times 10^6$

$F_{su} = 24.000(.9)$
$= 21,600 \, psi @ 160°F$
(1581/EPOXY @ ±45°
REF. MIL HDBK 17)[3]

$b = .648 + 2(.072)$
$= .792$

MJO NO 3027-001	SUBJECT		DATE 11/16/71	CHECKED BY 3:
TASK NO			CALCULATIONS BY A.M.T.	SHEET NO. 53

127

COMPOSITE HELICOPTER ROTOR HUB (CONT.)

SECTION B-B
COND. TW7F2

SHEAR ATTACHMENT OF UPPER PLATE
TO BASKET:

$$\Sigma EQ = EQ_{(13)} + EQ_{(14)}$$

$$= 2(5.107 + 1.100) \times 10^6$$

$$= 12.41 \times 10^6$$

$$q = \frac{V \Sigma EQ}{\Sigma \Sigma EI} \qquad\qquad \Sigma EI = 71.06 \times 10^6$$
$$\text{REF. Pg. } \underline{50}$$

$$= \frac{54840 (12.41 \times 10^6)}{2 (71.06 \times 10^6)}$$

$$= 4789 \text{ #/in ULT.}$$

$$f_s = \frac{q}{P} \qquad P = \text{BOND WIDTH}$$
$$\qquad\qquad = 1.0 \text{ in}$$
$$= 4789 \text{ psi ULT.}$$

$$F_{su} = 6500 \text{ psi (REF. WKR TEST DATA)}$$

$$M.S. = \frac{F_{su}}{f_s} - 1$$

$$= \frac{6500}{4789} - 1 = \quad\text{———}\quad \underline{\underline{+0.36}}$$

| MJO NO 3027-001 | SUBJECT | | DATE 11/17/71 | CHECKED BY ?·· |
| TASK NO | | | CALCULATIONS BY A.M.T. | SHEET NO 54 |

128

COMPOSITE HELICOPTER ROTOR HUB (CONT.)

SECTION B-B

CONU. TWIFZ

SHEAR ATTACHMENT OF LWR. PLATE

(ITEM ⑯ $\cancel{\phi}$ ⑲) TO BASKET (ITEM ⑰)

ITEM	A	E	AE	Y	AEY
18	.233	3.5	.816	2.16	1.76256
19	.140	4.4	.616	2.18	1.34288
					$\Sigma\ 3.105 \times 10^6$

AT BOND LINE (ITEM ① TO ITEM ②)

$$\Sigma EQ = 2(3.105 \times 10^6) = 6.210 \times 10^6$$

$$f_s = \frac{V \Sigma EQ}{\Sigma EI b}$$

$$b = 2(1.0) = 2.0 \text{ IN}$$

$$V = 59840 \text{ LBS ULT.}$$

$$\Sigma EI = 71.06 \times 10^6$$

(REF. PG. 50)

$$= \frac{59840 (6.210 \times 10^6)}{71.06 (2.0)}$$

$$= 2396 \text{ PSI ULT.}$$

$$\overline{F}_{su} = 6500 \text{ PSI}$$

$$M.S. = \frac{F_{su}}{f_s} - 1$$

$$= \frac{6500}{2396} - 1 = \underline{\qquad\qquad\qquad +1.71}$$

MJO NO	SUBJECT			DATE	CHECKED BY
8027-001				11/17/71	
TASK NO				CALCULATIONS BY	SHEET NO
				A.M.T.	55

129

COMPOSITE HELICOPTER ROTOR HUB (CONT.)

SECTION B-B

COND. TWTFZ

SHEAR STRESS IN UPPER PLATE (ITEM (14))

$$\Sigma EQ = 2\left[0.4(.156)(4.4 \times 10^6)(1.97) + .530(4.4 \times 10^6)(2.19)\right]$$

$$= 11.31 \times 10^6$$

$$f_s = \frac{V_N \Sigma EQ}{\Sigma E.I.(2b)}$$

$$= \frac{54840(11.31 \times 10^6)}{71.06 \times 10^6(.156)(2)}$$

$$= 27975 \, psi \; ULT.$$

$b = t = .156 \, (ITEM \; (14))$

$\Sigma ET = 71.06 \times 10^6$ (REF. PG. 50)

$V_N = 54840 \, LBS \; ULT.$

M.S. ~ NEGATIVE

∴ INCREASE TOP PLATE THICKNESS

COMPOSITE HELICOPTER ROTOR HUB (CONT.)

SECTION B-B
CONO TWIFZ .273

2.0

.156

₵

REVISED SECTION PROPERTIES ~

ITEM ④/⑭

22 PLIES 1581 E , t = 22(.009) = .198
10 PLIES SCOTCHPLY'S, t = 10(.0075) = .075
$t_{TOT} = 0.273$

$$E_{14} = \frac{t_{1581}\, E_{1581} + t_{SCOTCH}\, E_{SCOTCH}}{t_{TOT}}$$

$$= \frac{.198\,(6.2 \times 10^6) + .075\,(6.8 \times 10^6)}{.273}$$

$$= 3.5 \times 10^6$$

MJO NO 3022.001	SUBJECT			DATE 12/1/71	CHECKED BY JR
TASK NO				CALCULATIONS BY A.M.T.	SHEET NO. 51

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COMPOSITE HELICOPTER ROTOR HUB (CONT.)

SECTION B-B

COND. TW 7F2

REVISED SECTION PROPERTIES:

ITEM	A	E	AE	y	AEy	AEy²	EIo
Σ (REF. PG. 50)			14.326	—	31.99985	104.69165	2.33218
-13			-2.332	—	-.09561	-.00392	-.00472
-14			-.550	—	-.13200	-.03168	-.00111
+13 2.0(.16)=.312		4.4	1.373	.041	.05629	.00230	.00277
+14 1.0(.273)=.273		3.5	.956	.18	.17208	.03097	.00593
+20 1.0(.273)=.382		3.5	1.337	-.02	-.02674	.00053	.00830
			15.110		31.97387	104.68985	2.34335

$$\bar{y} = \frac{\Sigma AEy}{\Sigma AE}$$

$$= \frac{31.97387}{15.110} = 2.116$$

$$\Sigma EI = 2\left[\Sigma AEy^2 + \Sigma EIo - \bar{y}\Sigma AEy\right]$$

$$= 2\left[104.69 + 2.34 - 2.116(31.974)\right] \times 10^6$$

$$= 78.75 \times 10^6$$

@ CORNER OF ITEM ⑭ :

$$\Sigma EQ = 2\left[AE_{13} y_{13} + AE_A y_{19} + AE_{⑭} \cdot y_{⑭}\right]$$

$$= 2\left[1.373(2.075) + 1.331(2.136) + 0.4(.273)(3.5)(1.936)\right] \times 10^6$$

$$= 12.89 \times 10^6$$

MJO NO 3027-001	SUBJECT			DATE 12/1/71	CHECKED BY SY
TASK NO				CALCULATIONS BY A.M.T.	SHEET NO. 58

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COMPOSITE HELICOPTER ROTOR HUB (CONT.)

SECTION B-B
COND. TW7F2

SHEAR STRESS IN ITEM (14):

$$f_s = \frac{V_N \Sigma E Q}{\Sigma E I b},$$

$$= \frac{54840(12.89 \times 10^6)}{78.75 \times 10^6 (.546)}$$

$$= 16440 \text{ psi } ULT.$$

$V_N = 54840$ LBS ULT.

$b = 2(.273)$

$= .546$

$$F_s = \frac{t_{1581} F_{s_{1581}} + t_{scotch} F_{s_{scotch}}}{t_{TOT}}$$

$$= \frac{.198(21600) + .075(6200)}{.273}$$

$$= 17,900 \text{ psi}$$

$$M.S. = \frac{F_s}{f_s} - 1$$

$$= \frac{17,900}{16440} - 1 = \underline{\hspace{1cm}} \quad \underline{+ 0.09}$$

MJO NO 3027-001	SUBJECT				DATE 12/1/71	CHECKED BY 10
TASK NO					CALCULATIONS BY A.M.T.	SHEET NO. 59

COMPOSITE HELICOPTER ROTOR HUB (CONT.)

SECTION B-B
COND. TW7F2

SHEAR STRESS @ OUTB'D EDGE OF ITEM ⑬:

$$\Sigma EQ = 2\,AE_{13}\,y_{13}$$
$$= 2(1.373 \times 10^6)(2.075)$$
$$= 5.70 \times 10^6$$

$$f_s = \frac{V_N \Sigma EQ}{\Sigma EI\, b},$$

$$b = 2(.156)$$
$$= .312$$

$$\Sigma EI = 78.75 \times 10^6$$
$$(REF. \; P_{\!\!\!\!_{6.}} \; 58)$$

$$= \frac{54840 (5.70 \times 10^6)}{78.75 \times 10^6 (.312)}$$

$$= 12722 \; psi \; ULT.$$

$$F_s = \frac{t_{1581}\,F_{s_{1581}} + t_{scotch}\,F_{s_{scotch}}}{t_{TOT}}$$

$$= \frac{.081\,(21,600) + .075\,(8200)}{0.156}$$

$$= 15157 \; psi$$

$$M.S. = \frac{F_s}{f_s} - 1$$

$$= \frac{15157}{12722} - 1 = \underline{} \qquad +0.19$$

COMPOSITE HELICOPTER ROTOR HUB~

COND. TW7F2~ SYM. DIVE & PULLOUT
AUTOROTATION

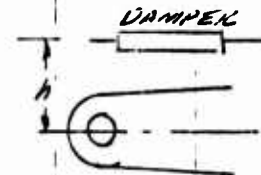REVISED BEARING GEOMETRY~

$a = 11.18$ $b = 10.40$

$c = 5.237$
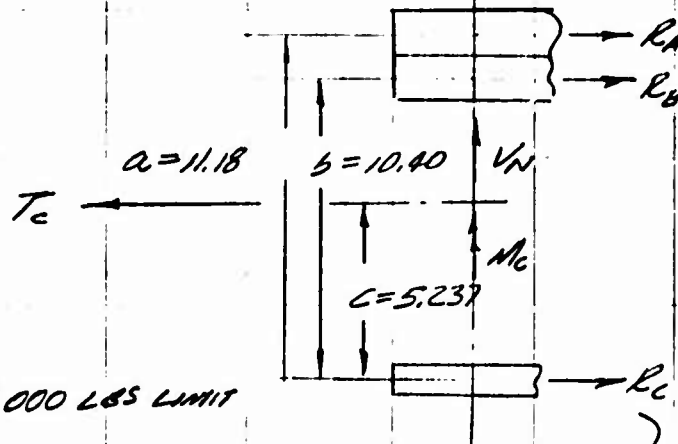
$T_c = 110\,000$ LBS LIMIT
$V_c = 0$
$V_N = 36560$ LBS LIMIT
$M_c = 72,000$ IN LBS LIMIT (VECTOR IS L/H RULE)

REF. SIKORSKY AIRCRAFT [1]
REF. SER 60514
PG. 13

HUB ARM AXIAL LOAD:

$$T_{c_{TOT}} = T_c + \frac{M}{h} \quad , \quad h = 9.412 \text{ IN}$$

DAMPER

$$= 110,000 + \frac{72,000}{9.412}$$

$$= 117,650 \text{ LBS LIMIT}$$

MJO NO 3027-001	SUBJECT			DATE 11/10/71	CHECKED BY S.M
TASK NO				CALCULATIONS BY A.M.T.	SHEET NO. 61

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COMPOSITE HELICOPTER ROTOR HUB~ (CONT.)

COND. TW7F2

BEARING LOADS (REF. TIMKEN ENGINEERING
JOURNAL, SECTION 2, Pg. 136 & 138) [7]

$$K_a = 1.24$$

$$K_b = 1.61$$

$$\Sigma M_c:$$

$$(R_A + R_B)\left(\frac{a+b}{2}\right) = T_{C_{TOT}}(c)$$

$$R_A + R_B = \frac{117650(5.237)}{\left(\frac{11.18 + 10.40}{2}\right)}$$

$$= 57102 \text{ LBS LIMIT}$$

$$\frac{0.47(R_A + R_B)}{K_a} = \frac{0.47(57102)}{1.24} = 21644 \text{ LBS LIMIT}$$

$$V_N = 36560 > 21644$$

$$\therefore R_B = 0 \text{ (REF. TIMKEN ENGINEERING JOURNAL,}$$
$$\text{SECTION 1, Pg. B-7) [7]}$$

$$\Sigma M_c:$$

$$R_A = \frac{117650(5.237)}{11.18} = 55110 \text{ LBS LIMIT}$$

$$R_C = T_{C_{TOT}} - R_A = 117650 - 55110 = 62540 \text{ LBS LIMIT}$$

MJO NO JC27-001	SUBJECT			DATE 11/10/71	CHECKED BY JCL
TASK NO				CALCULATIONS BY A.M.T.	SHEET NO. 62

COMPOSITE HELICOPTER ROTOR HUB (CONT.)

STRESS IN FILAMENT WOUND LUG STRAPS
AT VERTICAL AXIS:

FOR STATIC ANALYSIS, COND. TW7F2 IS
CRITICAL.

$$R_A = 55110 \text{ LBS LIMIT}$$
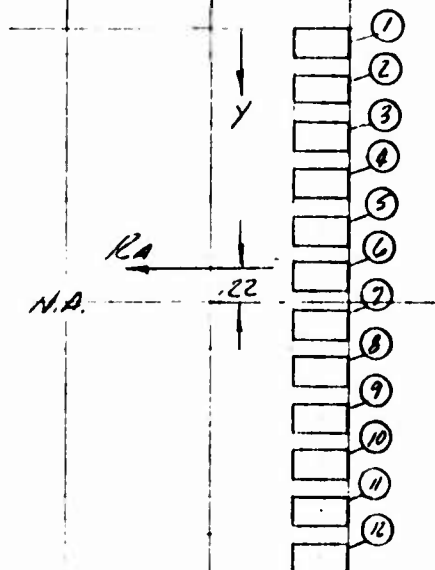$$= 82665 \text{ LBS. ULT.}$$

ITEM	Y	Y^2
1	.09	.0081
2	.41	.1681
3	.73	.5329
4	1.04	1.0816
5	1.36	1.8496
6	1.68	2.8224
7	2.00	4.0000
8	2.32	5.3824
9	2.64	6.9696
10	2.95	8.7025
11	3.27	10.6929
12	3.59	12.8881
	22.08	55.0982

$$\bar{Y} = \frac{\Sigma Y}{12} = \frac{22.08}{12} = 1.84$$

$$\Sigma Y^2_{NA} = \Sigma Y^2 - \bar{Y}\Sigma Y$$

$$= 55.0982 - 1.84(22.08)$$

$$= 14.47$$

MJO NO 3027-001	SUBJECT		DATE 11/6/71	CHECKED BY
TASK NO			CALCULATIONS BY A.M.T.	SHEET NO 63

COMPOSITE HELICOPTER ROTOR HUB (CONT.)

COND. TW.7F2
LUG STRAPS

$$P_n = \frac{M y_n}{\Sigma y^b} + \frac{R_n}{12}$$

STRAP NO. 1 HAS MAX
LOAD ~ BY INSPECTION

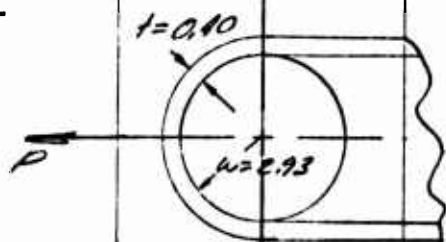$$P = \frac{18186\ (1.75)}{14.47} + \frac{82665}{12}$$

$$= 9088\ LBS\ ULT.$$

$$\frac{t}{a} = \frac{0.40}{2.93}$$
$$= 0.1365$$

$$\sigma_{AV} = \frac{P}{2tb}$$

$$= \frac{9088}{2(.40)(.19)}$$

$$= 59789\ psi\ ULT.$$

$$\sigma_{MAX} = 1.13\ \sigma_{AV}\ \frac{t}{a}$$, (REF. WKK R/O DEPT. USAAVLABS
TECH. REPT. 69-25, PG. 30) [2]

$$= 1.13\ (59789\ )(.1365)$$

$$= 9222\ psi\ ULT.$$

$M = R_a\ (0.22)$
$= 82665(.22)$
$= 18186\ in^{\#}\ ULT.$

$Y_1 = 1.84 - .09$
$= 1.75\ IN$

$t = 0.40$

$w = 2.93$

P

$b = STRAP\ THICKNESS$
$= 0.19$

138

COMPOSITE HELICOPTER ROTOR HUB ~ (CONT.)

COND. TWIFZ (CONT.)
LUG STRANS (CONT.)

$$\sigma_\theta = \left[1 + .079\left(\frac{t}{a}\right)^2\right]\sigma_{AVE}, \quad \left(\text{REF. USAAVLABS TECH REPT. } 69\text{-}26, \text{ Pg. 30}\right)[2]$$

$$= \left[1 + .079(.1365)^2\right] 59789$$

$$= 59877 \text{ psi ULT.}$$

$$\sigma_r^* = 25,000 \text{ psi}$$
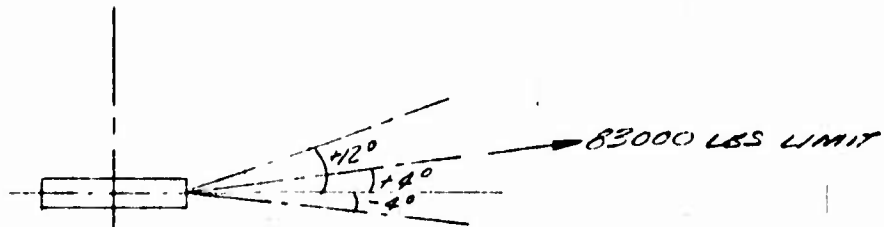$$\sigma_\theta^* = 180,000 \text{ psi}$$ SCOTCHPLY "3"

$$M.S. = \cfrac{1}{\left[\left(\cfrac{\sigma_r}{\sigma_r^*}\right)^2 - \cfrac{\sigma_r \sigma_\theta}{\sigma_r^* \sigma_\theta^*} + \left(\cfrac{\sigma_\theta}{\sigma_\theta^*}\right)^2\right]^{\frac{1}{2}}} - 1$$

$$= \cfrac{1}{\left[\left(\cfrac{-9222}{25000}\right)^2 - \cfrac{(-9222)(59877)}{(25000)(180,000)} + \left(\cfrac{59877}{180,000}\right)^2\right]^{\frac{1}{2}}} - 1$$

$$= \cfrac{1}{(.13607 + .12270 + .11065)^{\frac{1}{2}}} - 1$$

$$= \cfrac{1}{.6078} - 1 = \underline{\underline{+0.65}}$$

MJO NO 3027-001	SUBJECT				DATE 11/10/71	CHECKED BY SCS
TASK NO					CALCULATIONS BY A. M.T.	SHEET NO. 65

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COMPOSITE HELICOPTER ROTOR HUB~

FATIGUE LOADS~ (REF WRD REPT NO. 72-2-SOE [13]

CENTRIFUGAL FORCE = 63,000 LBS LIMIT
PER BLADE AT 185 RPM.

THE MEAN LAG ∡ IS APPROX 10° (MAX.)

$$V_{C_{MEAN}} = 63000 \, SIN \, 10°$$

$$= 14,413 \, LBS \, LIMIT$$

THE BLADE FLAPS FROM -4° TO +12°
DURING EACH ROTOR REVOLUTION

$$V_{N_{MEAN}}$$
$$POSITION = 83000 \, SIN \, 4°$$
$$= 5790 \, LBS \, LIMIT \, (ACTING \, UP)$$

$$V_{N_{MAX}} = 83000 \, SIN \, 12°$$
$$= 17257 \, LBS \, LIMIT$$

$$V_{N_{MIN}} = 83,000 \, SIN(-4°)$$
$$= -5790 \, LBS \, LIMIT$$

MJO NO. 3C27-001	SUBJECT	DATE 8/31/71	CHECKED BY _/c /_
TASK NO		CALCULATIONS BY _N. M.T._	SHEET NO. 66

COMPOSITE HELICOPTER ROTOR HUB

FATIGUE LOADS (CONT.)

THE STEADY STATE IN PLANE MOMENT IS:

$$M_{c_{STEADY}} = 36,000 \text{ IN LBS LIMIT}$$

CORIOLIS ACCELERATIONS DUE TO BLADE FLAPPING PRODUCE BLADE HUNTING WHICH IN TURN PRODUCES AN IN PLANE CYCLIC MOMENT~

$$M_{c_{CYCLIC}} = \pm 36000 \text{ IN LBS LIMIT}$$

$$M_{c_{MAX}} = M_{c_{STEADY}} + M_{c_{CYCLIC}}$$

$$= 36,000 + 36000$$

$$= 72000 \text{ IN LBS LIMIT}$$

$$M_{c_{MIN}} = 36,000 - 36,000$$

$$= 0$$

CORIOLIS ACCELERATIONS ARE ESTIMATED TO PRODUCE A CYCLICAL 2° LAG ANGLE.

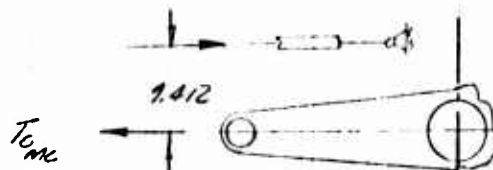$$V_{c_{CYLC}} = 83000 \sin 2° = 2900 \text{ LBS LIMIT (ALWAYS +)}$$

$$V_{c_{MAX}} = V_{c_{MEAN}} + V_{c_{CYC}} = 14413 + 2900 = 17313 \text{ LBS LIMIT}$$

$$V_{c_{MIN}} = V_{c_{MEAN}} = 14413 \text{ LBS LIMIT}$$

MJO NO 3027-001	SUBJECT			DATE 5/31/71	CHECKED BY IC L
TASK NO				CALCULATIONS BY A.M.T.	SHEET NO. 67

COMPOSITE HELICOPTER ROTOR HUB~
FATIGUE LOADS (CONT.)

RADIAL LOAD AT VERTICAL AXIS DUE TO M_c:

$$T_{C_{M_c}} = \frac{M_c}{9.412}$$

$$T_{C_{M_c\,MAX}} = \frac{72,000}{9.412} = 7650 \text{ LBS LIMIT}$$

$$T_{C_{M_c\,MIN}} = 0$$

$$T_{C_{TOT\,MAX}} = 83,000 + 7650 = 90,650 \text{ LBS LIMIT}$$

$$T_{C_{TOT\,MIN}} = 83,000 + 0 = 83,000 \text{ LBS LIMIT}$$

ALL CYCLIC LOADS ARE ASSUMED TO ACT IN
PHASE AND TO PRODUCE ONE CYCLE FOR EACH
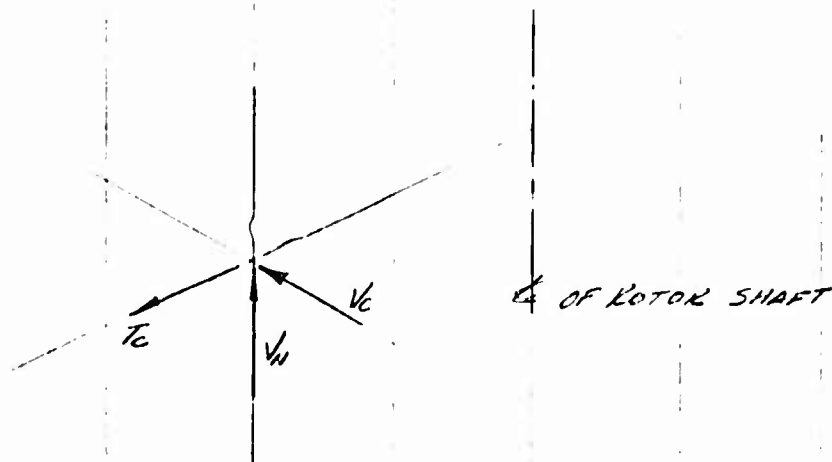ROTOR REVOLUTION.

M.J.O NO 3C27-001	SUBJECT			DATE 8/31/71	CHECKED BY R3
TASK NO				CALCULATIONS BY A.M.T.	SHEET NO. 68

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COMPOSITE HELICOPTER ROTOR HUB~
FATIGUE LOADS (CONT.)

SUMMARY ~ FATIGUE LOADS

	T_c	V_c	V_N
	LBS. ~ LIMIT		
MAX	90650	17313	17257
AVE	86825	15863	5721
MIN	83000	14413	-5790

V_c

T_c

V_N

₵ OF ROTOR SHAFT

MJO NO. 3027-001	SUBJECT	DATE 9/1/71	CHECKED BY 1.0
TASK NO		CALCULATIONS BY A. M.T.	SHEET NO. 69

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<u>COMPOSITE HELICOPTER ROTOR HUB (CONT.)</u>

<u>FATIGUE LOADS (CONT.)</u>

BEARING LOADS AT UPPER ARM:

FOR MAXIMUM FATIGUE CYCLE LOADS ~

$$T_{C_{TOT}} = \left(T_C^2 + V_C^2\right)^{\frac{1}{2}} = \left[(90650)^2 + (17313)^2\right]^{\frac{1}{2}} = 92288 \text{ LBS LIMIT}$$

$$V_{N_{MAX}} = 17257 \text{ LBS LIMIT}$$
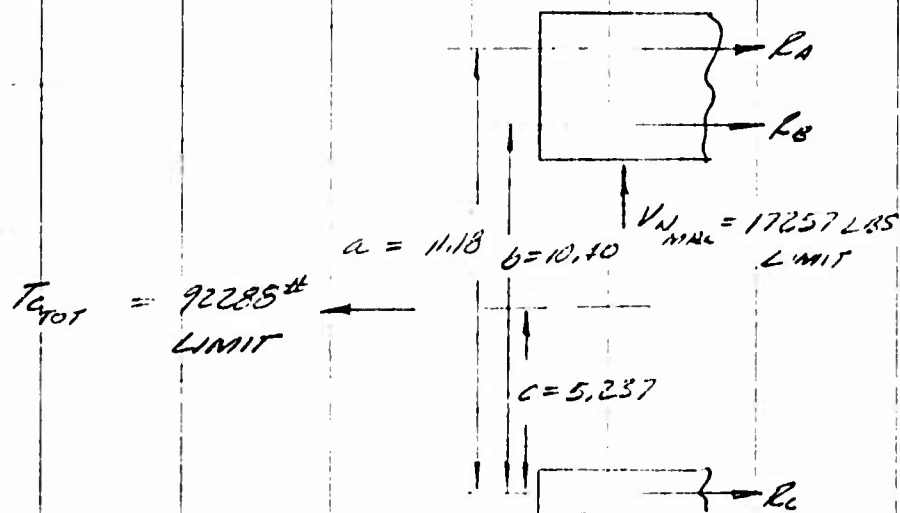
$$T_{C_{TOT}} = 92288^{\#} \text{ LIMIT}$$

$$a = 11.18 \qquad b = 10.40$$

$$V_{N_{MAX}} = 17257 \text{ LBS} \text{ LIMIT}$$

$$c = 5.237$$

$$\left(R_A + R_B\right)\left(\frac{11.18 + 10.40}{2}\right) = 92288(5.237)$$

$$R_A + R_B = 44773 \text{ LBS. LIMIT}$$

MJO NO 3027-001	SUBJECT			DATE 12/3/71	CHECKED BY A.S.
TASK NO				CALCULATIONS BY A.M.T.	SHEET NO 70

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COMPOSITE HELICOPTER ROTOR HUB (CONT.)
FATIGUE LOADS (CONT.)

BEARING LOADS AT UPPER ARM FOR
MAXIMUM FATIGUE CYCLE LOADS (CONT.)

IF: $V_A > \dfrac{0.47(R_A + R_B)}{R_A}$, (REF. TIMKEN ENG.
JOURNAL SECTION 1, [7]
Pg. B-7)

$17257. > \dfrac{0.47(44793)}{1.24}$

$\quad K_A = 1.24$
(REF. TIMKEN ENG.
JOURNAL, SECTION 2 [7]
Pg. 138)

$17257. > 16978$

THEN:
$R_B = 0$ (REF. TIMKEN ENG. JOURNAL [7])

WHEN $R_B = 0$
$R_A = \dfrac{92288(5.237)}{11.18} = 43230$ LBS LIMIT

BY RATIO OF $T_{C_{MAX}}$ TO T_C & V_C

$R_{A_{RADIAL}} = \dfrac{T_C}{T_{C_{MAX}}} R_A$

$= \dfrac{90650}{92288}(43230) = 42463$ LBS LIMIT

$R_{A_{TANGENTIAL}} = \dfrac{V_{N_{MAX}}}{T_{C_{MAX}}} R_A$

$= \dfrac{17257}{92288}(43230) = 8084$ LBS LIMIT

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COMPOSITE HELICOPTER ROTOR HUB (CONT.)

FATIGUE LOADS (CONT.)

BEARING LOADS AT UPPER ARM FOR
MINIMUM FATIGUE CYCLE LOADS ~

$$T_{C_{TOT}} = \left(T_C^2 + V_C^2\right)^{\frac{1}{2}}, \qquad T_{C_{MIN}} = 83,000^{\#} \text{ LIMIT} \left.\begin{array}{c} \\ \end{array}\right\} \text{REF.}$$

$$= \left[(83000)^2 + (14413)^2\right]^{\frac{1}{2}} \quad V_{C_{MIN}} = 14413^{\#} \text{ LIMIT} \left.\begin{array}{c} \\ \end{array}\right\} \text{PG. } \underline{69}$$

$$= 80242 \text{ LBS LIMIT}$$

$$(R_A + R_B)\left(\frac{11.18 + 10.40}{2}\right) = 84242 \ (5.237)$$

$$R_A + R_B = 40887 \text{ LBS LIMIT (TRIAL VALUE)}$$

THRUST (V_N) IS NEGATIVE & ACTS PRIMARILY
ON BEARING B.

$$K_B = 1.61, \quad \left(\text{REF. TIMKEN ENGINEERING}\right.$$
$$\left.\text{JOURNAL, SECTION } C^{[7]} \text{ PG. } 136\right)$$

IF: $\quad V_N < \dfrac{0.47 (R_A + R_B)}{K_B}, \quad V_N = 5790^{\#} \text{ LIMIT}$
$$\text{ACTING DOWN}$$
$$(\text{REF. PG. } \underline{69})$$

$$5790 < \frac{0.47(40887)}{1.61}$$

$$5790 < 11936$$

THEN: BOTH BEARINGS ARE LOADED

MJO NO 5027-001	SUBJECT	DATE 12/3/71	CHECKED BY LCF
TASK NO		CALCULATIONS BY A.M.T.	SHEET NO. 72

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COMPOSITE HELICOPTER ROTOR HUB (CONT.)

FATIGUE LOADS (CONT.)

BEARING LOADS AT UPPER ARM FOR
MINIMUM FATIGUE CYCLE LOADS~

RADIAL LOADS ON BEARINGS PRODUCE
THRUST LOADS (REF. TIMKEN ENGINEERING
JOURNAL, SECTION 1) [7]

$$V_{N_B} = \frac{0.47 R_B}{K_B} \quad , \quad V_{N_A} = \frac{0.47 R_A}{K_A}$$

$\Sigma F_V :$

$$\frac{0.47 R_B}{K_B} - \frac{0.47 R_A}{K_A} = V_N$$

$$R_B = \frac{K_B}{0.47} \left[V_N + \frac{0.47 R_A}{K_A} \right]$$

$$= \frac{1.61}{0.47} \left[5790 + \frac{0.47 R_A}{1.24} \right]$$

$$= 19834 + 1.29837 R_A \qquad (1)$$

$\Sigma M_C :$ (SEE SKETCH PG. ___)

$10.40 R_B + 11.18 R_A = T_{C_{TOT}} (5.237)$, $T_{C_{TOT}} = 84242$ LBS LIMIT (REF PG. 21)

BY SUBSTITUTION FROM (1):

$$10.40 (19834 + 1.29837 R_A) + 11.18 R_A = 84242 (5.237)$$

$$206274 + 13.503 R_A + 11.18 R_A = 441175$$

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COMPOSITE HELICOPTER ROTOR HUB (CONT.)

FATIGUE LOADS (CONT.)

BEARING LOADS AT UPPER ARM FOR
MINIMUM FATIGUE CYCLE LOADS (CONT.) ~

$$R_A = \frac{441175 - 206274}{13.503 + 11.18}$$

$$= 9517 \ LBS \quad LIMIT$$

$$R_B = 19834 + 1.29837(9517)$$

$$= 32191 \ LBS. \quad LIMIT$$

CHECK:

ΣF_V:

$$\frac{0.47 R_B}{K_B} - \frac{0.47 K_A}{K_A} = V_N$$

$$\frac{0.47(32191)}{1.61} - \frac{0.47(9517)}{1.24} = 5790$$

$$9397 - 3607 = 5790 \ \checkmark$$

ΣM:

$$10.40(32191) + 11.18(9517) = 84242(5.237)$$

$$441186 = 441175 \ \checkmark$$

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COMPOSITE HELICOPTER ROTOR HUB (CONT.)

FATIGUE LOADS (CONT.)

MINIMUM FATIGUE CYCLE LOADS (CONT.)

$$R_{A_{RADIAL}} = \frac{83,000}{84242}(9517) = 9377 \text{ LBS LIMIT}$$

$$R_{A_{TANGENTIAL}} = \frac{14413}{84242}(9517) = 1628 \text{ LBS LIMIT}$$

$$R_{B_{RADIAL}} = \frac{83000}{84242}(32191) = 31716 \text{ LBS LIMIT}$$

$$R_{B_{TANGENTIAL}} = \frac{14413}{84242}(32191) = 5508 \text{ LBS LIMIT}$$

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COMPOSITE HELICOPTER ROTOR HUB (CONT.)

FATIGUE LOADS (CONT.)

_SUMMARY ~ FATIGUE LOADS ON HUB
ARM AT VERTICAL AXIS_

LOCATION	APPLIED LOADS LBS ~ LIMIT	
	MAX.	MIN.
R_{AR}	42063	9377
R_{AT}	8084	1628
R_{AV}	17257(UP)	3607(UP)
R_{BR}	0	31716
R_{BT}	0	5508
R_{BV}	0	-9397(DN)

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COMPOSITE HELICOPTER ROTOR HUB ~

FATIGUE STRESS IN FILAMENT-WOUND

ITEMS AT VERT AXIS ~

ITEM	y	y^2
1	.095	.00902
2	.413	.17056
3	.731	.53436
4	1.049	1.10040
5	1.367	1.86868
6	1.685	2.83922
7	2.003	4.01200
8	2.321	5.38704
9	2.639	6.94432
10	2.957	8.74384
11	3.275	10.72562
12	3.593	12.90964
	22.128	55.24470

$$\bar{y} = \frac{\Sigma y}{12} = \frac{22.128}{12} = 1.844$$

$$\Sigma y^2_{N.A.} = \Sigma y^2 - \bar{y}\Sigma y$$

$$= 55.24470 - 1.844(22.128)$$

$$= 19.461$$
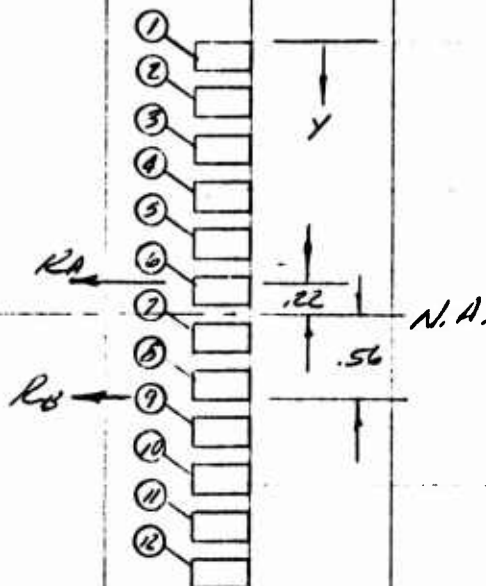
$$P_n = \frac{M y_n}{\Sigma y^2} + \frac{R_a + R_b}{12}$$

COMPOSITE HELICOPTER ROTOR HUB ~

FATIGUE STRESS IN FILAMENT- WOUND
ITEMS AT VERTICAL AXIS (CONT.)

FOR FATIGUE CYCLE MAX LOADS ~

$$M = R_A(.22) - R_B(.56),$$

$$M = 43226(.22)$$

$$= 9510 \, in^{\#} \; LIMIT$$
$$(TENSION \; IN \; UPPER$$
$$STRAPS)$$

$$R_A = \left(R_{A_R}^2 + R_{A_T}^2\right)^{1/2}$$

$$= \left[(42463)^2 + (8084)^2\right]^{1/2}$$

$$= 43226^{\#} \; LIMIT$$
$$(REF. \; Pa. \; \underline{76})$$

$$R_B = 0 \; (REF. \; P. \; \underline{76})$$

MAX LOAD OCCURS IN STRAP
NO. ①

$$P_① = \frac{My_①}{\Sigma y_{N.A.}^2} + \frac{R_A}{12} \quad ,$$

$$= \frac{9510 \cdot (1.749)}{14.461} + \frac{43226}{12}$$

$$= 4752 \; LBS. \; LIMIT$$

$$y_① = \bar{y} - y_1$$
$$= 1.844 - .095$$
$$= 1.749 \, IN.$$

$$\sigma_{AV} = \frac{P_①}{2 \, t \, b} \quad ,$$

$$= \frac{4752}{2(.19)(.40)} = 31263 \; psi \; LIMIT$$
$$(@ \; CYCLE \; MAX. \; LOAD)$$

$$t = 0.40 \, IN$$
$$b = 0.19 \, IN$$

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COMPOSITE HELICOPTER ROTOR HUB ~

FATIGUE STRESS IN STRAP No ① (CONT.)

$$\sigma_r = 1.13 \, \bar{\sigma}_{AV} \left(\frac{t}{a}\right) \quad \text{(REF. USAAVLABS TECH}$$
$$\text{REPORT 69-25, } \text{Fig. 30})$$

$$= 1.13 \, (31263) \left(\frac{.40}{2.93}\right) \quad t = 0.40$$

$$= 4825 \, psi \text{ LIMIT COMPR.}$$
$$\text{(@ CYCLE MAX LOADS)}$$

$$\sigma_\theta = \left[1 + .079 \left(\frac{t}{a}\right)^2\right] \bar{\sigma}_{AV}$$

(REF. USAAVLABS
TECH. REPT. 69-25, Fig. 30)

$$= \left[1 + .079 \left(\frac{.40}{2.93}\right)^2\right] (31263)$$

$$= 1.00147 \, (31263)$$

$$= 31309 \, psi \text{ LIMIT}$$
$$\text{(@ CYCLE MAX LOADS)}$$

$a = 2.93$

$t = 0.40$

$b =$ STRAP THICKNESS
$= 0.190$

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COMPOSITE HELICOPTER ROTOR HUB ~

FATIGUE STRESS IN STRAP NO. ① (CONT.)

FOR FATIGUE CYCLE MINIMUM LOADS ~

$$M = R_A(.22) - R_B(.56), \qquad R_A = \left(R_{A_R}^2 + R_{A_T}^2\right)^{1/2}$$

$$= 9517(.22) - 32191(.56) \qquad = \left[(9377)^2 + (1628)^2\right]^{1/2}$$

$$= -15933 \text{ in}^\# \text{ LIMIT} \qquad = 9517 \text{ LBS LIMIT}$$

(COMPR. IN UPPER STRAPS) (REF. PG. 26) FOR R_{A_R} & R_{A_T})

$$P_① = \frac{M y_①}{\Sigma Y_{N.A.}^2} + \frac{R_A + R_B}{12} \qquad R_B = \left[R_{B_R}^2 + R_{B_T}^2\right]^{1/2}$$

$$= \left\{(31716)^2 + (5508)^2\right\}^{1/2}$$

$$= \frac{-15933(1.749)}{14.461} + \frac{(9517 + 32191)}{12}, \qquad = 32191 \text{ LBS LIMIT}$$

(REF. PG. 26) FOR R_{B_R} & R_{B_T})

$$= 1549 \text{ LBS LIMIT (TENSION)}$$

$$\sigma_{AV.} = \frac{P_①}{2+b}$$

$$= \frac{1549}{2(.40)(.19)}$$

$$= 10191 \text{ psi LIMIT (@ CYCLE MIN LOAD)}$$

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TASK NO			CALCULATIONS BY A.M.T.	SHEET NO. 80

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COMPOSITE HELICOPTER ROTOR HUB~

FATIGUE STRESS IN STRAP NO. ① (CONT.)

$$\sigma_r = 1.13\, \sigma_{AV}\left(\frac{t}{a}\right)$$

$$= 1.13\,(10191)\left(\frac{.40}{2.93}\right)$$

$$= 1572\ PSI \ LIMIT \ (@ \ CYCLE \ MIN. \ LOADS)$$
COMPRESSION

$$\sigma_\theta = \left[1 + .079\left(\frac{t}{a}\right)^2\right]\sigma_{AV}$$

$$= \left[1 + .079\left(\frac{.40}{2.93}\right)^2\right]10191$$

$$= 10206\ PSI \ LIMIT \ (@ \ CYCLE \ MIN. \ LOADS)$$

SUMMARY~ FATIGUE STRESS IN STRAP NO. ①

$$\sigma_{\theta_{MAX}} = 31309\ PSI \qquad \sigma_{r_{MAX}} = -1572\ PSI$$

$$\sigma_{\theta_{MIN}} = 10206\ PSI \qquad \sigma_{r_{MIN}} = -4823\ PSI$$

$$\sigma_{\theta_{MEAN}} = 20757.5\ PSI \qquad \sigma_{r_{MEAN}} = -3197.5\ PSI$$

$$\sigma_{\theta_{ALT}} = 10551.5\ PSI \qquad \sigma_{r_{ALT.}} = 1625.5\ PSI$$

$$R_\theta = \frac{\sigma_{\theta_{MIN}}}{\sigma_{\theta_{MAX}}} \qquad R_r = \frac{\sigma_{r_{MIN}}}{\sigma_{r_{MAX}}}$$

$$= \frac{10206}{31309} \qquad = \frac{-4823}{-1572}$$

$$= 0.326 \qquad = 3.07$$

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COMPOSITE HELICOPTER ROTOR HUB~

FATIGUE STRESS IN STRAP NO. (12)

FOR FATIGUE CYCLE MAX. LOADS~

$$M = R_A(.22) - R_B(.56),$$

$$M = 43226(.22)$$

$$= 9510 \text{ IN}^{\#} \text{ LIMIT}$$

(COMPR. IN LWR. STRAP)

$R_A = 43226^{\#} \text{ LIMIT}$

(REF. PG. 78)

$R_B = 0$

$$P_{(12)} = \frac{-M Y_{(12)}}{\Sigma Y_{N_0}^2} + \frac{R_A}{12}$$

$$= \frac{9510(-1.749)}{14.461} + \frac{43226}{12}$$

$$= 2452 \text{ LBS LIMIT}$$

$Y_{(12)} = \bar{Y} - Y_{12}$

$= 1.844 - 3.593$

$= -1.749$

$$\sigma_{AV} = \frac{P_{(12)}}{2 t b},$$

$$= \frac{2452}{2(0.40)(0.19)}$$

$$= 16131 \text{ PSI LIMIT}$$

(@ CYCLE MAX. LOAD)

$t = 0.40$

$b = 0.19$

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5027-001						
TASK NO					CALCULATIONS BY A.M.T.	SHEET NO. 82

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COMPOSITE HELICOPTER ROTOR HUB ~

FATIGUE STRESS IN STRAP NO. ⑫ (CONT.)

$$\sigma_r = 1.13 \, \sigma_{AV} \left(\frac{t}{a} \right)$$

$$= 1.13 \, (16131) \left(\frac{.40}{2.93} \right)$$

$$= 2488 \, psi \, LIMIT$$

(@ CYCLE MAX. LOAD)

$$\sigma_\theta = \left[1 + .079 \left(\frac{t}{a} \right)^2 \right] \sigma_{AV}$$

$$= \left[1 + .079 \left(\frac{.40}{2.93} \right)^2 \right] (16131)$$

$$= 16155 \, psi \, LIMIT$$

(@ CYCLE MAX. LOADS)

FOR FATIGUE CYCLE MINIMUM LOADS ~

$M = -15933 \, in^{\#} \, LIMIT$ (REF. PG. __80__)

$$P_{⑫} = \frac{M \, y_{(12)}}{\Sigma \, y^2_{N.A.}} + \frac{R_a + R_b}{12} \quad , \qquad R_a = 9517^{\#} \, LIMIT$$

(REF. PG. __80__)

$$= \frac{-15933 \, (-1.749)}{14.461} + \frac{(9517 + 32191)}{12} \quad R_b = 32191^{\#} \, LIMIT$$

(REF. PG. __80__)

$$= 5903^{\#} \, LIMIT \, (TENSION) \qquad y_{(12)} = -1.749$$

(REF. PG. __82__)

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COMPOSITE HELICOPTER ROTOR HUB —

FATIGUE STRESS IN STRAP NO. ⑫ (CONT.)

$$\sigma_{AV} = \frac{P_{⑫}}{2tb}$$

$$= \frac{5903}{2(.140)(.19)}$$

$$= 35546 \, psi \; LIMIT$$
$$(@ \; CYCLE \; MIN. \; LOAD)$$

$$\sigma_r = 1.13 \, \sigma_{AV} \left(\frac{t}{a}\right)$$

$$= 1.13(35546)\left(\frac{.140}{2.93}\right)$$

$$= 5484 \, psi \; LIMIT$$
$$(@ \; CYCLE \; MIN \; LOAD)$$

$$\sigma_\theta = \left[1 + .079\left(\frac{t}{a}\right)^2\right]\sigma_{AV.}$$

$$= \left[1 + .079\left(\frac{.140}{2.93}\right)^2\right]35546$$

$$= 35598 \, psi \; LIMIT$$
$$(@ \; CYCLE \; MIN \; LOADS)$$

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TASK NO				CALCULATIONS BY A.M.T.	SHEET NO. 84

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COMPOSITE HELICOPTER ROTOR HUB~

SUMMARY ~ FATIGUE STRESS IN STRAP No. (12)

$$\sigma_{\theta MIN} = 16155 \ psi \qquad \sigma_{r MIN} = -5484 \ psi$$

$$\sigma_{\theta MAX} = 35598 \ psi \qquad \sigma_{r MAX} = -2488 \ psi$$

$$\sigma_{\theta MEAN} = 25876 \ psi \qquad \sigma_{r MEAN} = -3986 \ psi$$

$$\sigma_{\theta ALT.} = 9721.5 \ psi \qquad \sigma_{r ALT} = 1498 \ psi$$

$$R_{\theta} = \frac{\sigma_{\theta MIN}}{\sigma_{\theta MAX}} \qquad R_{r} = \frac{\sigma_{r MIN}}{\sigma_{r MAX}}$$

$$= \frac{16155}{35598} \qquad = \frac{-5484}{-2488}$$

$$= 0.454 \qquad = 2.20$$

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COMPOSITE HELICOPTER ROTOR HUB —

FATIGUE ALLOWABLE STRESSES ~

A CONSTANT LIFE FATIGUE DIAGRAM
FOR UNIDIRECTIONAL "S" GLASS/EPOXY
LAMINATES LOADED PARALLEL TO THE
FIBERS IS DRAWN BASED ON DATA
OBTAINED FROM AFML TECHNICAL
REPT. TR-64-403.[8] THIS CONSTANT LIFE
FATIGUE DIAGRAM IS SHOWN ON PG. 87.
A 0.5 REDUCTION FACTOR TO ACCOUNT FOR
SIZE EFFECT, SURFACE EFFECT, DATA SCATTER,
ETC. IS USED TO PRODUCE A WORKING
GOODMAN DIAGRAM FROM THE CONSTANT
LIFE FATIGUE DIAGRAM. THIS WORKING
GOODMAN DIAGRAM IS SHOWN ON PG. 88.

S/N DIAGRAMS FOR STRAP NO ① & STRAP
NO. ⑫ ARE CONSTRUCTED AT APPROPRIATE
STRESS RATIOS (R). THESE DIAGRAMS ARE
SHOWN ON PAGES 89 & 90. FAILURE
INITIATION TIME'S FOR STRAP NO. ① &
STRAP NO. ⑫ FATIGUE AXIAL STRESSES ARE
THEN CALCULATED.

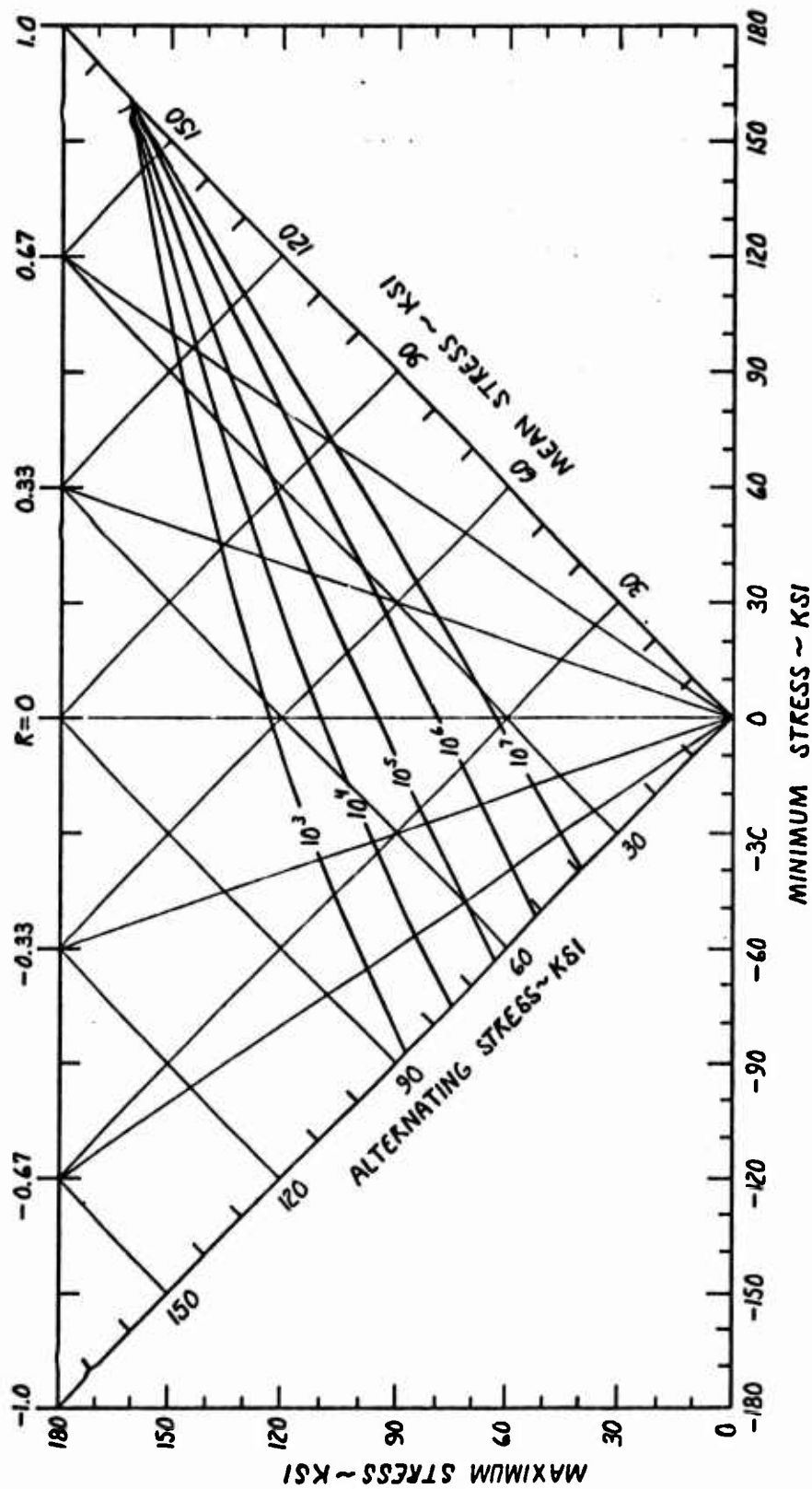| MJO NO 3027-001 | SUBJECT | | | DATE 12/15/71 | CHECKED BY |
| TASK NO | | | | CALCULATIONS BY A.M.T. | SHEET NO. 86 |

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Figure 39. Constant Life Fatigue Diagram for Unidirectional S-Glass/Epoxy Laminate - Axial Load Parallel to Fibers.
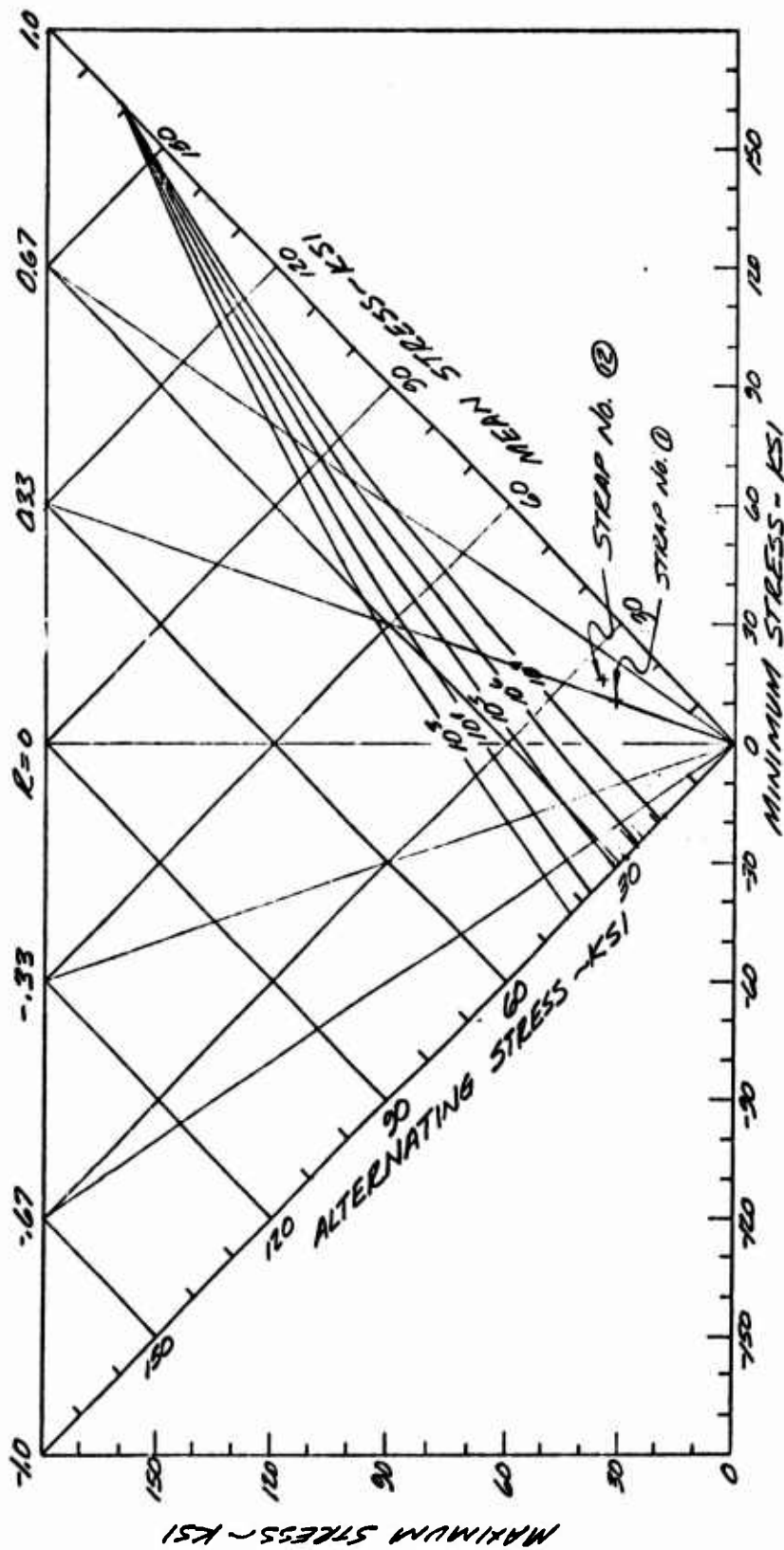
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Figure 40.   Working Goodman Fatigue Diagram - Unidirectional S-Glass/Epoxy
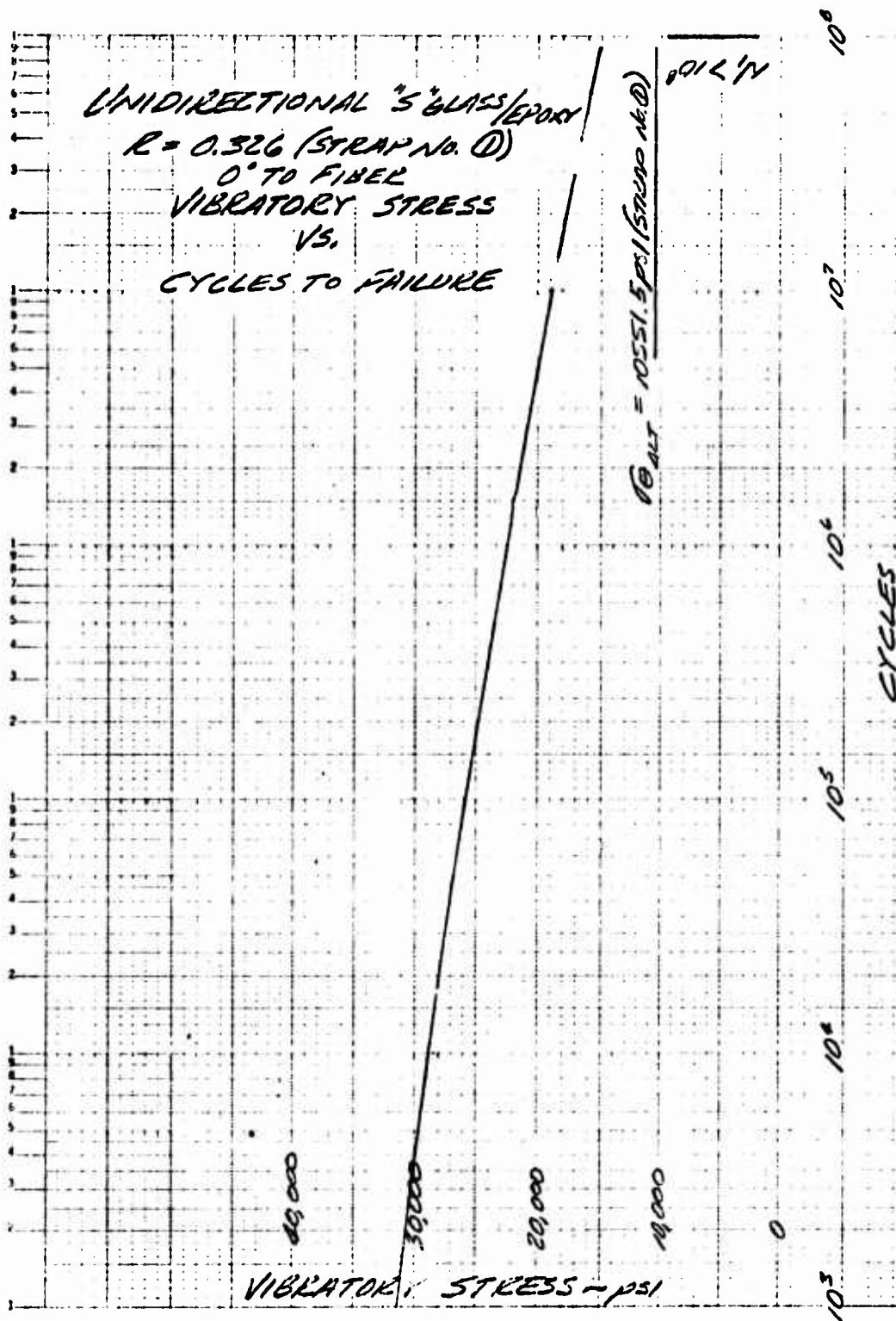Laminate - Axial Load Parallel to Fibers.

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Figure 41. Unidirectional S-Glass/Epoxy, R = 0.325 (Strap No. 1), 0° to Fiber, Vibratory Stress Vs. Cycles to Failure.
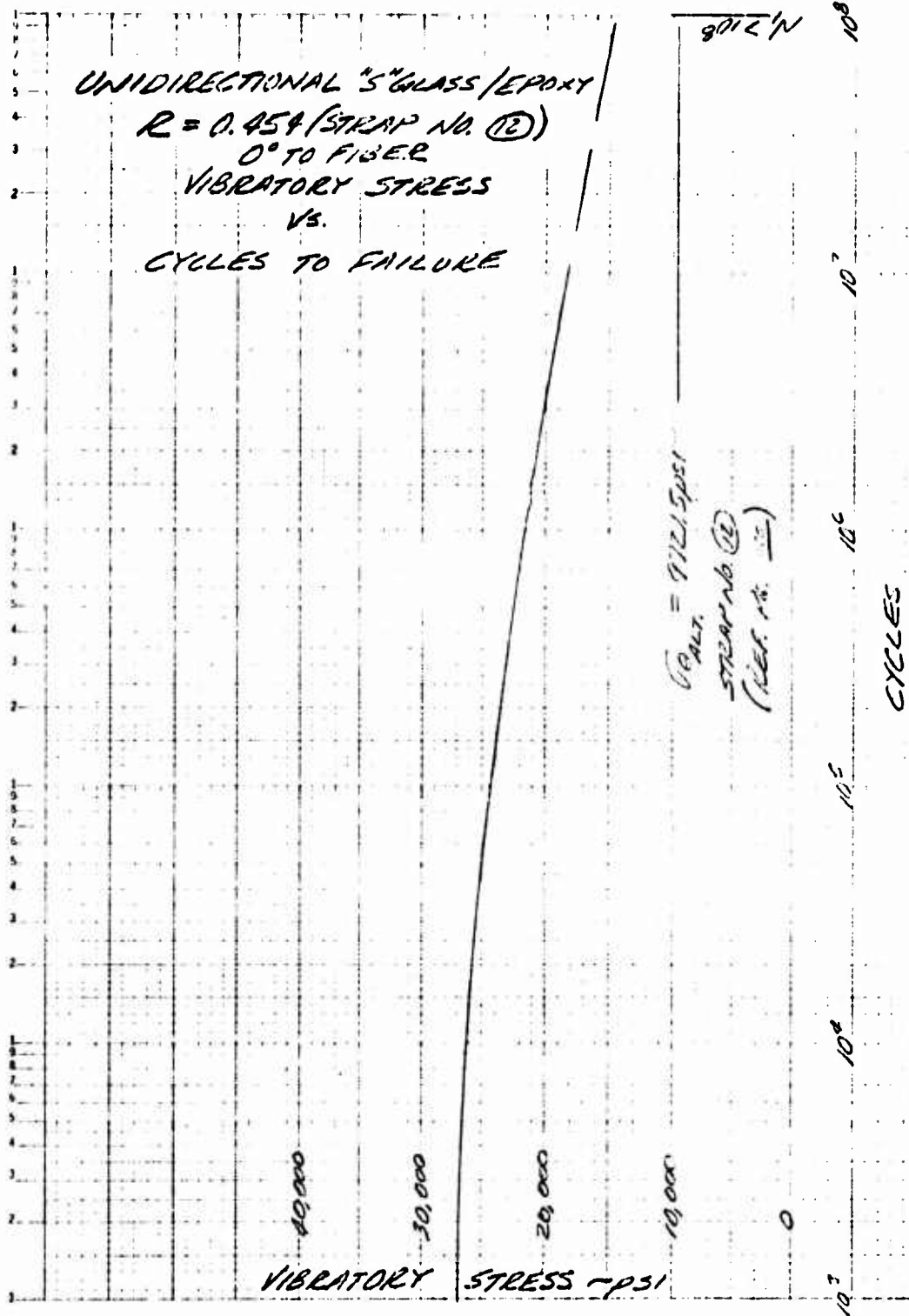
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Figure 42. Unidirectional S-Glass/Epoxy, R = 0.454 (Strap No. 12), 0° to Fiber, Vibratory Stress Vs. Cycles to Failure.

COMPOSITE HELICOPTER ROTOR HUB

FAILURE INITIATION TIME FOR STRAP No. ①
FATIGUE STRESS @ 0° TO FIBER:

APPLIED CYCLES/100 HRS:

$$n_1 = 1 \, cyc./rev \times 185 \, rev/min \times 60 \, min/hr \times 100$$

$$= 1.110 \times 10^6 \, cyc./100 \, hrs.$$

ALLOWABLE CYCLES:
STRAP No. ①, $R = 0.326$, $\sigma_{ALT} = 10551.5 \, psi$ (REF. Pg. 81)

$$N_1 > 10^8 \, (REF. Pg. 103)$$

$$DAMAGE/100 \, HRS = \frac{n_1}{N_1} = \frac{1.110 \times 10^6}{> 10^8} < 0.0111$$

$$FAILURE \; INITIATION \; TIME = \frac{100}{DAMAGE/100 \, HRS}$$

$$= \frac{100}{< 0.0111} = > 9000 \, HRS.$$

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COMPOSITE HELICOPTER ROTOR HUB~

FAILURE INITIATION TIME FOR STRAP NO. (12)
FATIGUE STRESS @ 0° TO FIBER:

APPLIED CYCLES/100 HRS:

$n_1 = 1.110 \times 10^6$ CYC./100 HRS (REF. CALC. Pg. 91)

ALLOWABLE CYCLES:

STRAP NO. (12), $R = 0.454$, $\sigma_{0_{ALT}} = 9721.5$ PSI

$$N_1 > 10^8 \text{ (REF. Pg. 124)} \qquad \text{(REF. Pg. 85)}$$

$$\text{DAMAGE/100 HRS} = \frac{n}{N_1} = \frac{1.110 \times 10^6}{> 10^8} \doteq < 0.0111$$

FAILURE INITIATION TIME = 100/DAMAGE/100 HRS.

$$= \frac{100}{< 0.0111} = > \underline{\underline{9000 \text{ HRS.}}}$$

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TASK NO						CALCULATIONS BY A. M. T.	SHEET NO. 92

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<u>COMPOSITE HELICOPTER ROTOR HUB</u>

<u>FATIGUE ALLOWABLE STRESSES ~</u>

A CONSTANT LIFE FATIGUE DIAGRAM
FOR UNIDIRECTIONAL "S" GLASS/EPOXY
LAMINATES LOADED PERPENDICULAR TO
THE FIBERS IS DRAWN BASED ON DATA
OBTAINED FROM FOREST PRODUCTS LAB
REPT. NO. 1823-B[9], FIG. 43. FATIGUE STRESSES
PERPENDICULAR TO THE FIBERS ARE RESIN
SENSITIVE AS ARE STRESSES AT 45° TO THE
WARP FOR CLOTH LAMINATES. THEREFORE,
45° DATA WERE USED. A WORKING GOODMAN
DIAGRAM IS DRAWN USING A REDUCTION FACTOR
OF 0.5. S/N DIAGRAMS FOR STRAPS NO. ① & ⑩
ARE DRAWN FOR APPROPRIATE STRESS
RATIOS (R) AND TIME TO FAILURE INITIATION
CALCULATED

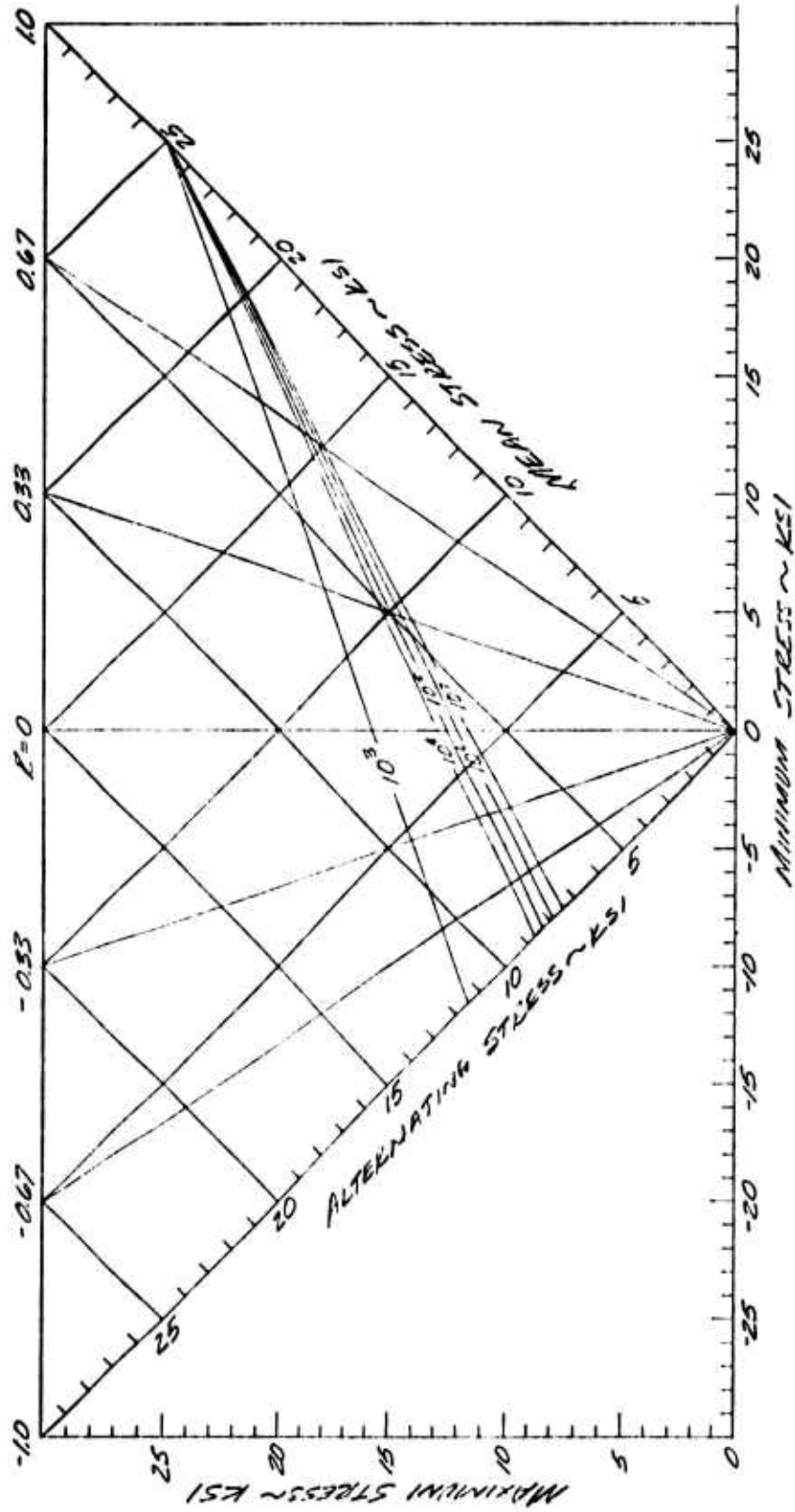| MJO NO. 3027-001 | SUBJECT | DATE 12/15/71 | CHECKED BY |
| TASK NO. | | CALCULATIONS BY A.M.T. | SHEET NO. 93 |

Figure 43. Constant Life Fatigue Diagram – Unidirectional S-Glass/Epoxy Laminate – Loaded Perpendicular to Fibers.
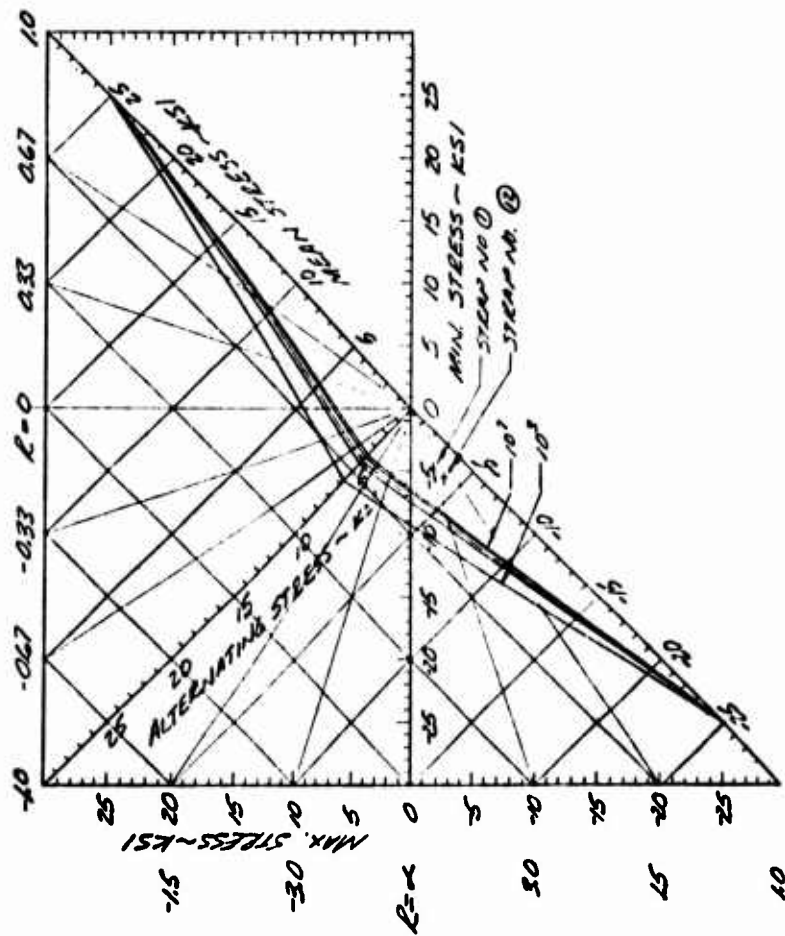
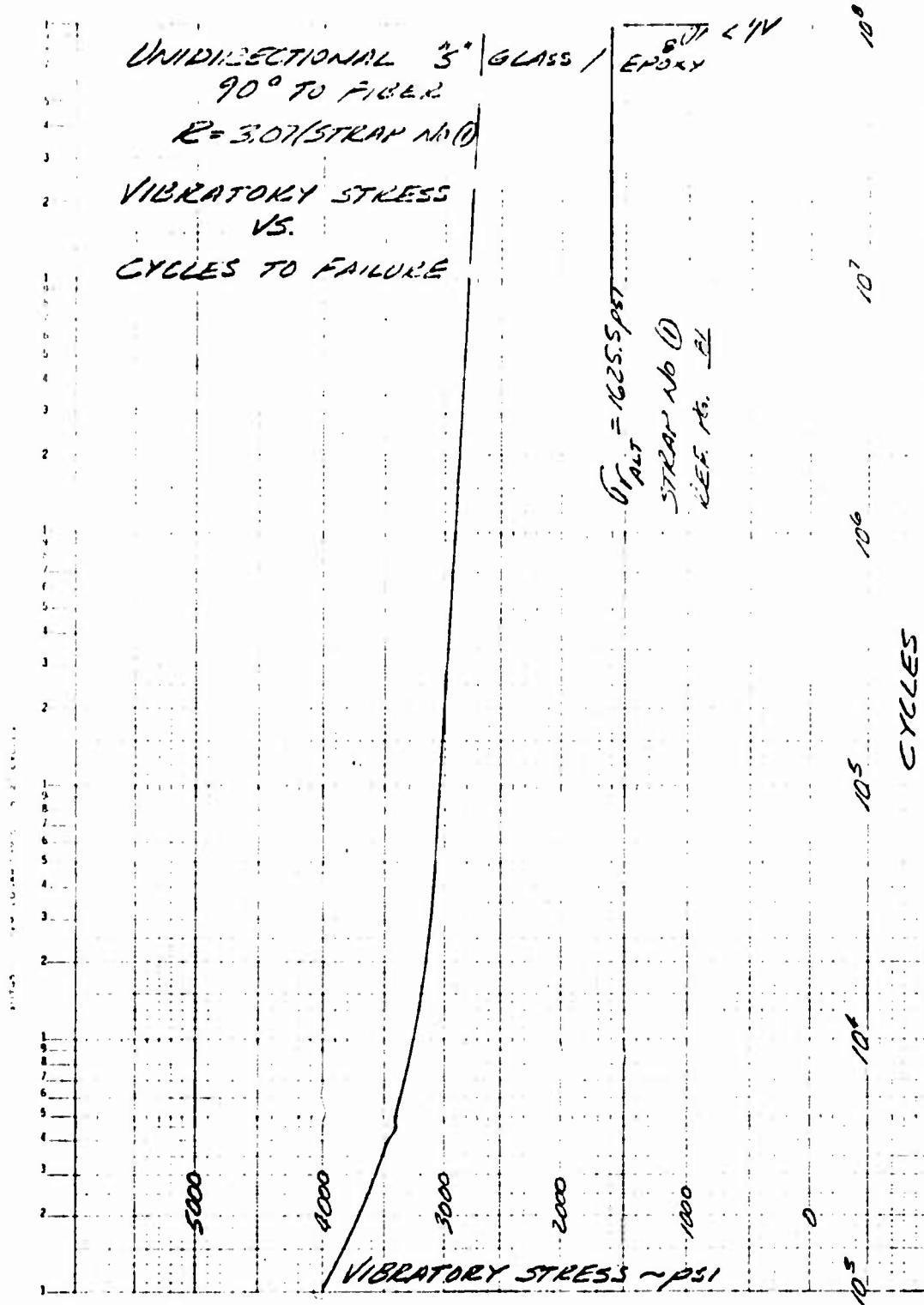Figure 44. Working Goodman Fatigue Diagram - Unidirectional S-Glass/Epoxy Laminate - Loaded Perpendicular to Fibers.

Figure 45. Unidirectional S-Glass/Epoxy, R = 3.07 (Strap No. 1),
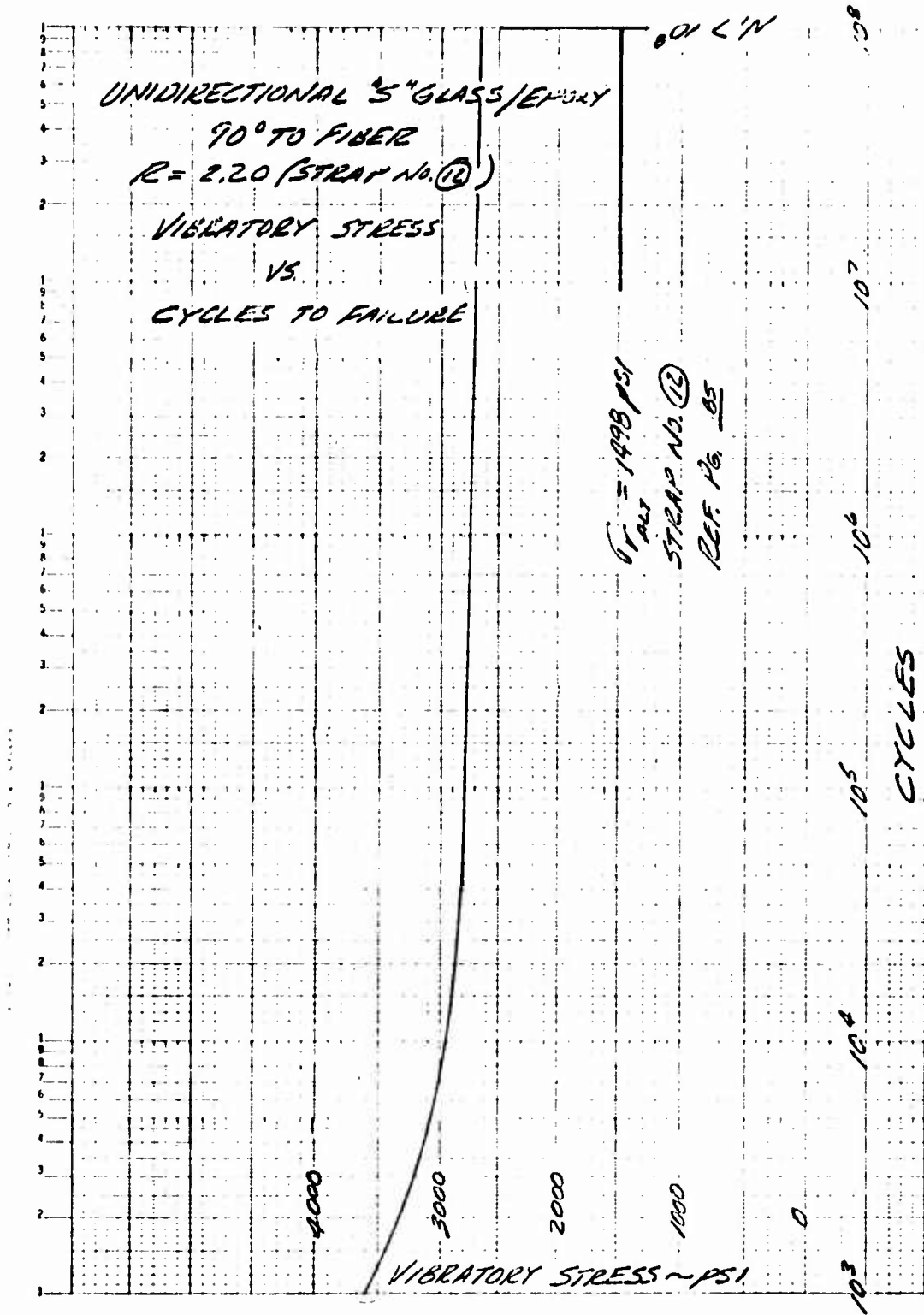90° to Fiber, Vibratory Stress Vs. Cycles to Failure.

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Figure 46. Unidirectional S-Glass/Epoxy, R = 2.20 (Strap No. 12),
90° to Fiber, Vibratory Stress Vs. Cycles to Failure.

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COMPOSITE HELICOPTER ROTOR HUB ~

FAILURE INITIATION TIME FOR STRAP No. ①
FATIGUE STRESS @ 90° TO FIBER

FOR $R_r = 3.07$, $\sigma_{ALT} = 1625.5 \, psi$ (REF. P. 81)

$N_i > 10^8$ CYCLES (REF. P. 96)

FAILURE INITIATION TIME > 9000 HRS.
(REF. CALC. P. 91)

FAILURE INITIATION TIME FOR STRAP No. ⑫
FATIGUE STRESS @ 90° TO FIBER

FOR $R_r = 2.20$, $\sigma_{ALT} = 1498 \, psi$ (REF. P. 85)

$N_i > 10^8$ CYCLES (REF. P. 97)

FAILURE INITIATION TIME > 9000 HRS.

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TASK NO				CALCULATIONS BY A.M.T.	SHEET NO. 98

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COMPOSITE HELICOPTER ROTOR HUB~

FATIGUE STRESS IN SHEAR AT SECTION B-B
(REF. PG. _41_ , ITEM ⑯ AT N.A.)

FOR CYCLE MAXIMUM LOADS~

$V_{N_{MAX}}$ = 17257 LBS LIMIT (REF. PG. _69_)

@ N.A. ITEM ⑯

$$f_S = \frac{V_{N_{MAX}}}{V_{N_{COND. TWIST}}} \left(f_{S_{COND. TWIST}} \right)$$

$V_{N_{COND. TWIST}}$ = 54840 LBS.
(REF. PG. _9_)

$f_{S_{COND. TWIST}}$ = 20287 psi
(REF. PG. _52_)

$$= \frac{17257}{54840} (20287)$$

$$= 6384 \text{ psi LIMIT}$$

FOR CYCLE MINIMUM LOADS~

$V_{N_{MIN}}$ = -5790 LBS. LIMIT (REF. PG. _69_)

$$f_S = \frac{V_{N_{MIN}}}{V_{N_{COND. TWIST}}} \left(f_{S_{COND. TWIST}} \right)$$

$$= \frac{-5790}{54840} (20287)$$

$$= -2142 \text{ psi LIMIT}$$

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COMPOSITE HELICOPTER ROTOR HUB ~

FATIGUE STRESS IN SHEAR AT SECTION B-B (CONT.)

SUMMARY ~

$$f_{s_{MAX}} = 6384\ psi$$

$$f_{s_{MIN}} = -2142\ psi$$

$$f_{s_{MEAN}} = 2121\ psi$$

$$f_{s_{ALT.}} = 4263\ psi$$

$$R = \frac{f_{s_{MIN}}}{f_{s_{MAX.}}} = \frac{-2142}{6384} = -0.335$$

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TASK NO				CALCULATIONS BY A.M.T.	SHEET NO. 100

COMPOSITE HELICOPTER ROTOR HUB~

FATIGUE ALLOWABLE STRESSES~

A CONSTANT LIFE FATIGUE DIAGRAM FOR 1581 E GLASS/EPOXY LAMINATES UNDER AXIAL FATIGUE LOADS AT 0° TO THE WARP IS DRAWN FROM DATA IN WADC TR 55-389.[10] A CONSTANT LIFE FATIGUE DIAGRAM FOR 1581 E/EPOXY LAMINATES LOADED IN SHEAR AT 45° TO THE WARP IS THEN OBTAINED BY THE RATIO:

$$\left(\frac{F_{ALT.}}{F_{TU}}\bigg/_{1581}\right)_{\substack{1581 \\ 0° TO WARP}} \times F_{SU_{\substack{1581 \\ 45° TO WARP}}}$$

AT APPROPRIATE VALUES FOR N & R. A WORKING GOODMAN DIAGRAM IS THEN DRAWN USING A REDUCTION FACTOR OF 0.5. AN S/N DIAGRAM IS DRAWN AND FAILURE INITIATION TIME CALCULATED.

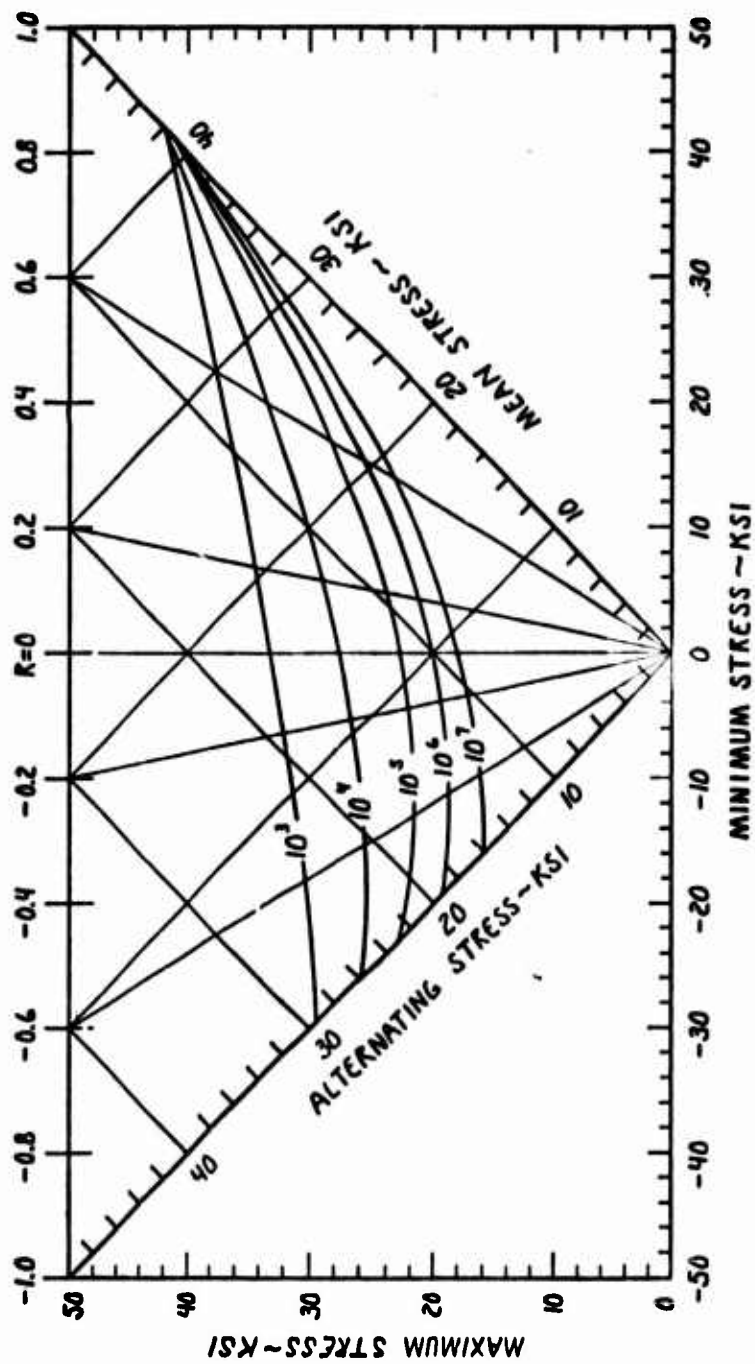| MJO NO 3027-001	SUBJECT				DATE 12/15/71	CHECKED BY
TASK NO					CALCULATIONS BY A.M.T.	SHEET NO. 101

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Figure 47. Constant Life Fatigue Diagram for 1581 E-Glass/Epoxy Laminate Axial Load, 0° to Warp.

176
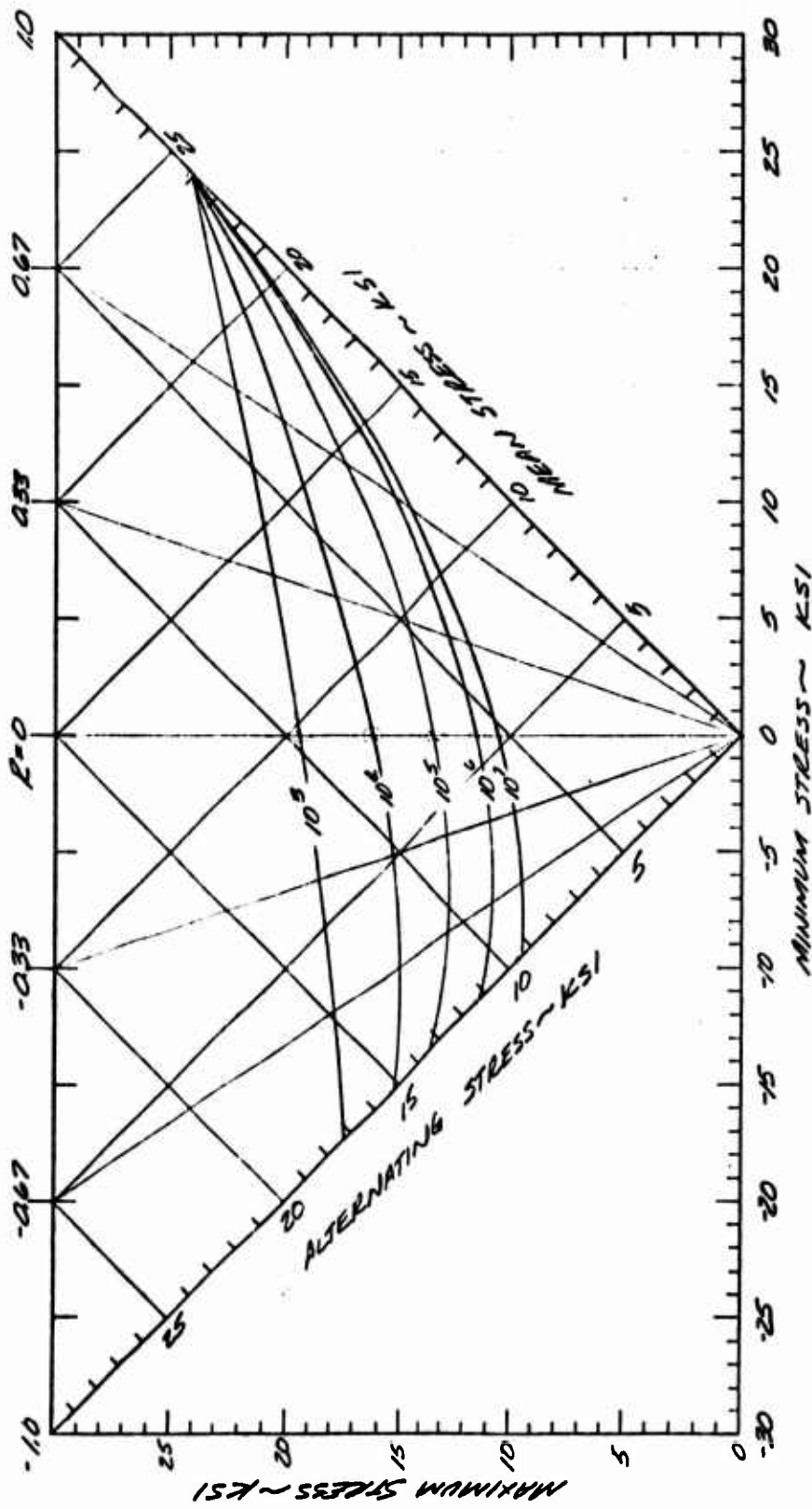
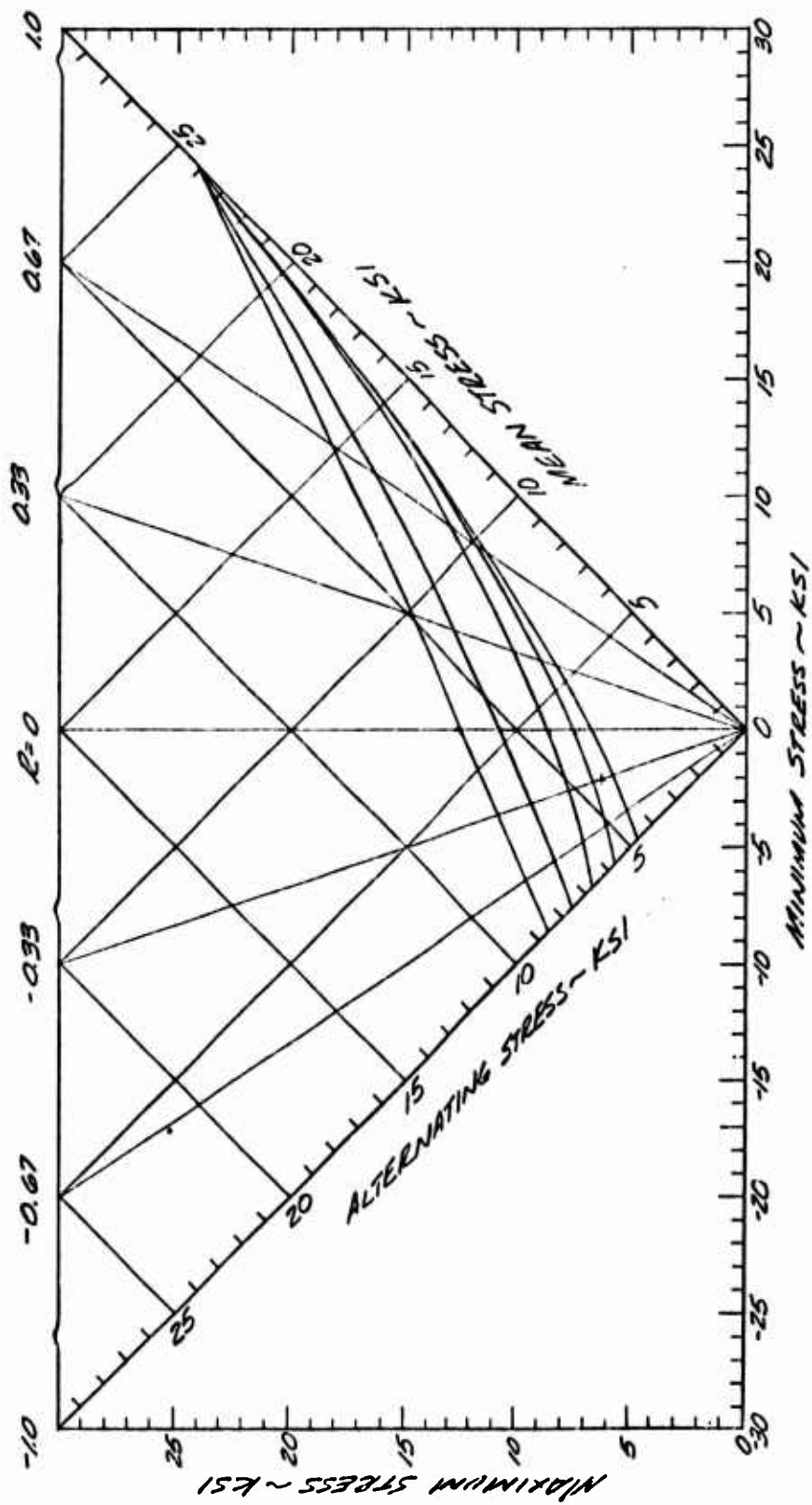Figure 48. Constant Life Fatigue Diagram for 1581 E-Glass/Epoxy Laminate in Shear at ± 45° to Warp.

Figure 49. Working Goodman Fatigue Diagram - 1581 E-Glass/Epoxy
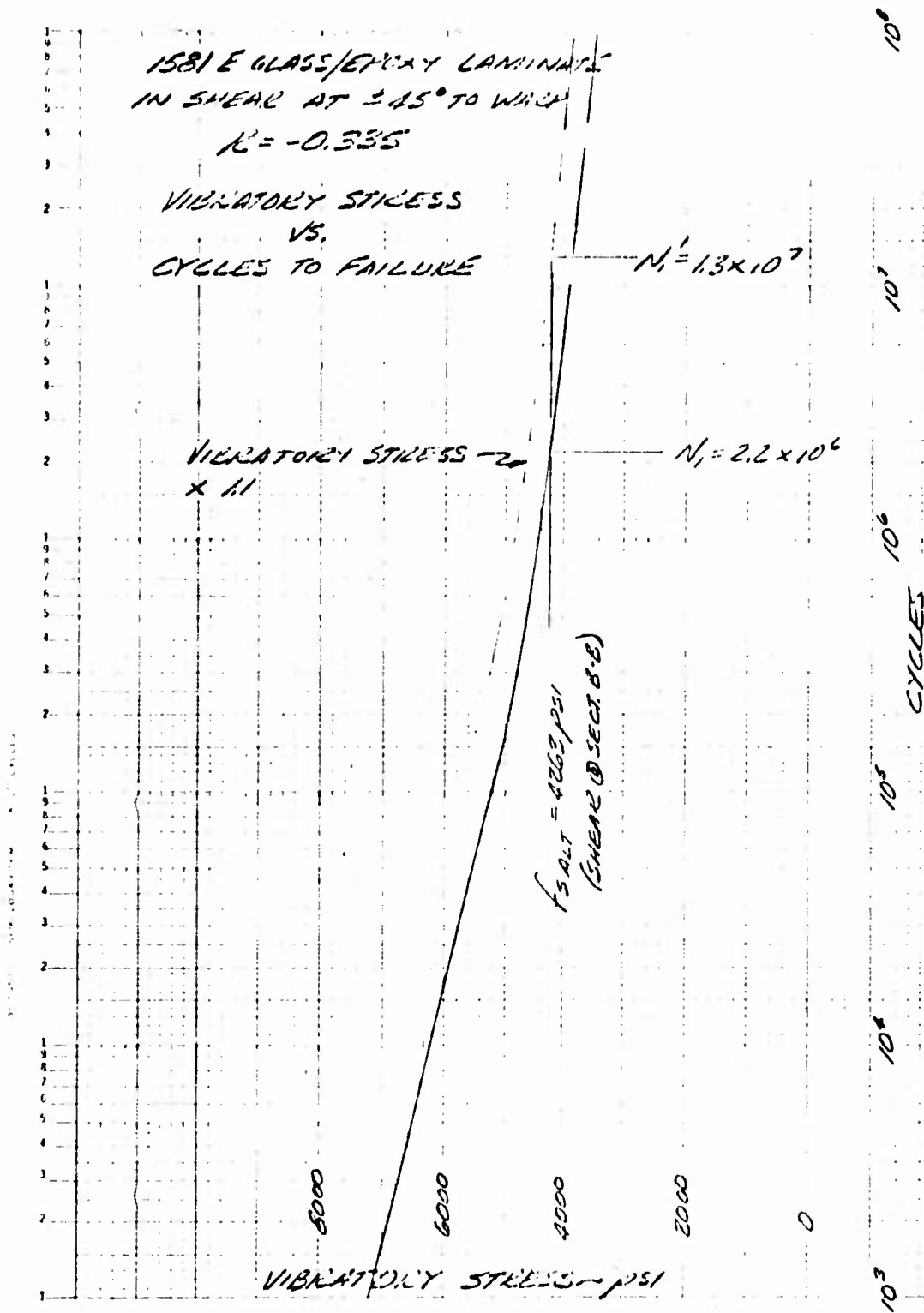Laminate in Shear at ± 45° to Warp.

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1581 E GLASS/EPOXY LAMINATE
IN SHEAR AT ±45° TO WARP

$k' = -0.335$

VIBRATORY STRESS
VS.
CYCLES TO FAILURE

$N_1' = 1.3 \times 10^7$

VIBRATORY STRESS
× 1.1

$N_1 = 2.2 \times 10^6$

$f_{s\, ALT} = 4263\, PSI$
(SHEAR @ SECT 6-6)

VIBRATORY STRESS — PSI

CYCLES

Figure 50. 1581 E-Glass/Epoxy Laminate in Shear at ±45° to Warp,
R = 0.335, Vibratory Stress Vs. Cycles to Failure.

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Composite Helicopter Rotor Hub ~

FAILURE INITIATION TIME FOR SHEAR
FATIGUE STRESS IN ITEM ⑯ AT SECT. B·B

ALLOWABLE CYCLES:

FOR $R = -0.335$, $f_{S_{ALT}} = 4263$ psi (REF. Pg. 100)

$N_1 = 2.2 \times 10^6$ (REF. Pg. 105)

APPLIED CYCLES/100 HRS. :

$n_2 = 1.110 \times 10^6$ cyc./100 HRS. (REF. CALC. Pg. 91)

DAMAGE/100 HRS. $= \dfrac{n_2}{N_1} = \dfrac{1.110 \times 10^6}{2.2 \times 10^6} = 0.5045$

FAILURE INITIATION TIME $= \dfrac{100}{DAMAGE/100 HRS}$

$= \dfrac{100}{0.5045}$

$= \underline{198\ HRS.}$

THIS CALCULATED FAILURE INITIATION TIME
IS SMALLER THAN DESIRED. HOWEVER, THE
GOODMAN DIAGRAM AND THE S/N CURVE
FOR 1581 E GLASS/EPOXY IS ESTIMATED BY RATIO
FROM AXIAL STRESS DIAGRAMS & IS FELT TO
BE CONSERVATIVE. A SMALL UPWARD

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COMPOSITE HELICOPTER ROTOR HUB~

SHEAR FATIGUE STRESS IN ITEM ⑯ (CONT.)

SHIFT IN THE ALLOWABLE VIBRATORY STRESS
IN THE S/N CURVE GIVES A LARGE INCREASE
IN FAILURE INITIATION TIME. FOR EXAMPLE,
IF ALLOWABLE VIBRATORY STRESS IS INCREASED
10%, $N_1' = 1.3 \times 10^7$ (REF. PG. 108)

THEN:

$$\text{DAMAGE}/100 \text{ HRS} = \frac{n_1}{N_1} = \frac{1.110 \times 10^6}{1.3 \times 10^7} = .0854$$

$$\text{FAILURE INITIATION TIME} = \frac{100}{\text{DAMAGE}/100 \text{ HRS.}}$$

$$= \frac{100}{.0854}$$

$$= 1170 \text{ HRS.}$$

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COMPOSITE HELICOPTER ROTOR HUB~

ADDENDUM TO STRESS ANALYSIS

DISCUSSION~

IN THE COURSE OF PROTOTYPE FABRICATION,
SOME DESIGN CHANGES WERE MADE TO
ACCOMMODATE FABRICATION PROCESSES. IN
ADDITION, STUDY OF A HIGH STRESS -
LOW CYCLE (GAG CONDITION) FATIGUE
REGIME AS WELL AS THE LOW STRESS
HIGH CYCLE (CRUISE CONDITION) FATIGUE
REGIME WAS FELT TO BE DESIRABLE.

THE FOLLOWING ANALYSIS EXAMINES STRESSES
IN THE REVISED STRUCTURE FOR STATIC
AND FATIGUE LOADS.

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COMPOSITE HELICOPTER ROTOR HUB (CONT.)
REVISED CROSS-SECTION
SECTION PROPERTIES ~ SECT. A·A
(10.9 IN OUTBD OF HUB ₵)

$X_{\textcircled{13}} = 2.27$

$\bar{y} = 2.317$

$X_{\textcircled{16}} = 3.50$

$X_{\textcircled{18}} = 3.6\sim$

N.A.

Y
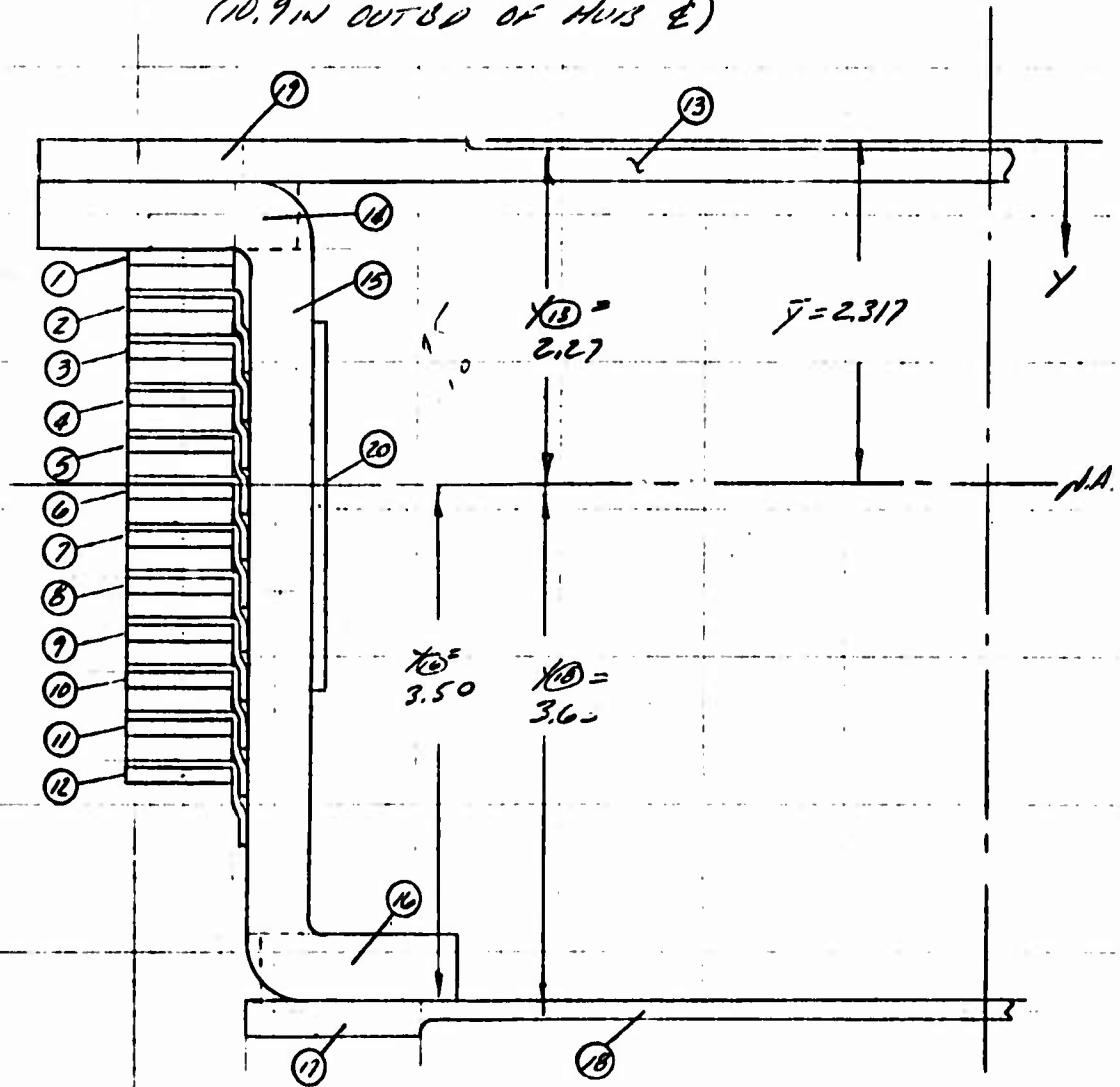
MJO NO. 3027-001	SUBJECT		DATE 7/13/72	CHECKED BY
TASK NO.)			CALCULATIONS BY A.M.T.	SHEET NO. 109

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COMPOSITE HELICOPTER ROTOR HUB (CONT.)
REVISED LAYUPS ~
BOTTOM PLATE (ITEM ⑦)

8 PLIES 1581 @ ±45°, t = .072
21 PLIES SCOTCHPLY, t = 0.158
$$t_{TOT} = 0.230$$

$$E = \frac{t_{45}' E_{1581_{\pm 45}} + t_o E_{SCOTCHPLY}}{t_{TOT}}$$

$$= \frac{.072(2.2 \times 10^6) + 0.158(6.8 \times 10^6)}{0.230}$$

$$= 5.4 \times 10^6 \, psi$$

BASKET (ITEMS ⑭, ⑮, ⑯ & ⑳)

$$E = 1.78 \times 10^6, \quad 1543 \text{ "E" EPOXY CROSSPLIED}$$
$$@ \pm 45° \text{ TO WARP (REF. MIL HDBK 17}[3]$$
$$TABLE 2-1)$$

MJO NO. 3027-C02	SUBJECT	DATE 7/10/72	CHECKED BY
TASK NO		CALCULATIONS BY A.M.T.	SHEET NO. 110

COMPOSITE HELICOPTER ROTOR HUB (CONT.)

REVISED SECTION PROPERTIES ~ SECTION A-A (CONT.)

ITEM	A	$E \times 10^6$	$AE \times 10^6$	y	$AEy \times 10^6$	$AEy^2 \times 10^6$	$EJ_0 \times 10^6$
1	.15×10=.075	6.8	0.510	0.80	.40800	.32640	.00042
2				1.12	.57120	.63974	
3				1.43	.72930	1.04289	
4				1.75	.89250	1.56187	
5				2.07	1.05570	2.18529	
6				2.38	1.21380	2.88884	
7				2.70	1.37700	3.71790	
8				3.03	1.54530	4.68225	
9				3.34	1.70340	5.63935	
10				3.66	1.86660	6.83175	
11				3.98	2.02980	8.07860	
12	.075	6.8	0.510	4.31	2.19810	9.47381	.00042
13	.22×.367=.822	5.1	4.192	0.16	.67072	.10731	.01751
14	.05×.382=.019	1.78	1.458	0.49	.71442	.35006	.02459
15	.15×1.63=2.084	1.78	3.710	3.03	11.24130	34.06113	6.16512
16	.15×1.35=.621	1.78	1.105	5.59	6.17695	34.52915	.01865
17	1.2×1.230=.288	5.4	1.555	5.95	9.25225	55.05088	.00694
18	.39×.117=.463	3.9	1.806	5.88	10.61928	62.44136	.00205
19	3.0×.269=.807	4.6	3.712	0.13	0.98256	.06273	.02237
20	2.5×.119=.298	1.78	0.441	2.48	1.09368	2.71232	.22945
			24.099		55.34186	236.03363	6.95162

COMPOSITE HELICOPTER ROTOR HUB (CONT.)

REVISED SECTION PROPERTIES ~ SECT. A-A (CONT.)

$$\bar{y} = \frac{\Sigma AEy}{\Sigma AE}$$

$$= \frac{55.84186 \times 10^6}{24.099 \times 10^6}$$

$$\bar{y} = 2.317 \text{ IN}$$

$$\Sigma EI = 2 \left[\Sigma AEy^2 + \Sigma EI_0 - \bar{y} \Sigma AEy \right]$$
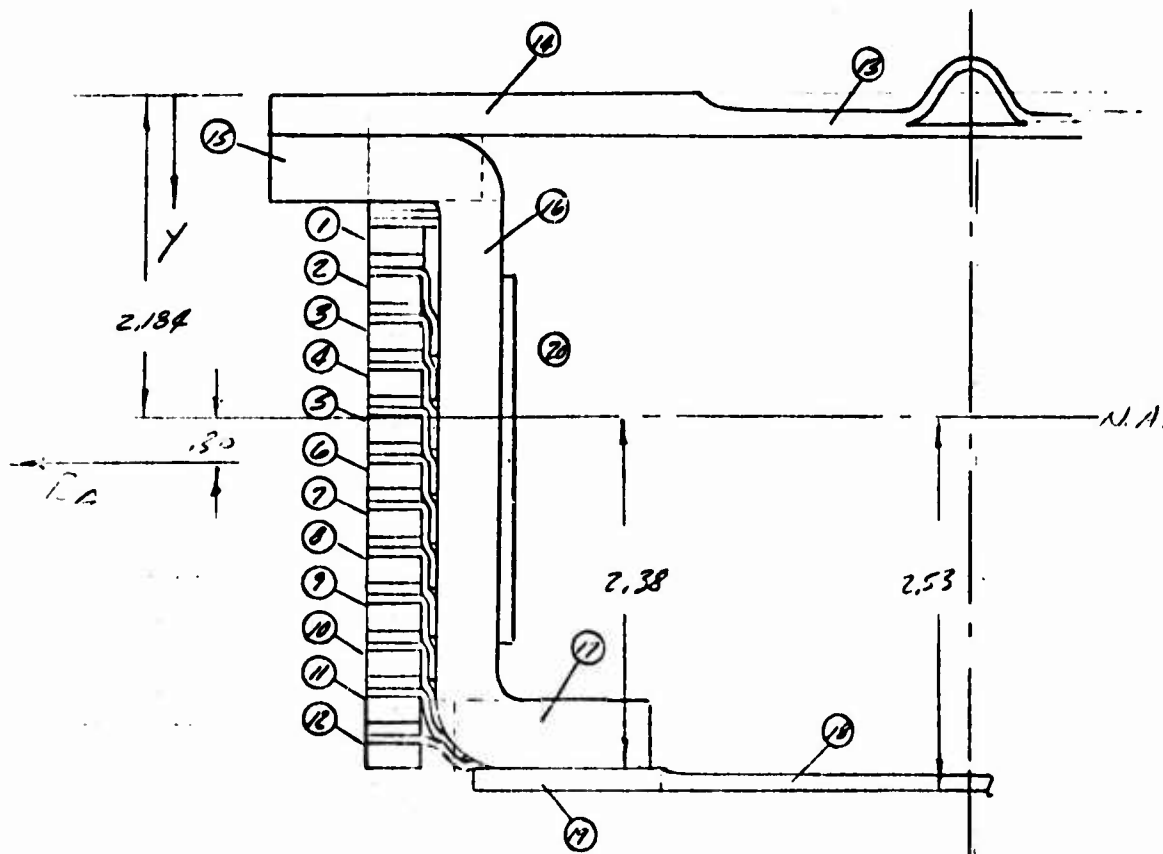
$$= 2 \left[236.43 + 6.95 - (2.317)(55.842) \right] \times 10^6$$

$$\Sigma EI = 227.99 \times 10^6$$

$$\Sigma AE = 2 (24.099 \times 10^6)$$

$$= 48.20 \times 10^6$$

MJO NO 3027-001	SUBJECT				DATE 7/17/72	CHECKED BY 3
TASK NO.					CALCULATIONS BY A.M.T.	SHEET NO. 112

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COMPOSITE HELICOPTER ROTOR HUB (CONT.)

SECTION B-B (17.9 IN OUTB'D OF HUB ℄)

REVISED CROSS-SECTION

MJO NO. $DC7-001$	SUBJECT	DATE $7/18/72$	CHECKED BY a
TASK NO.		CALCULATIONS BY $A.M.T.$	SHEET NO. 113

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COMPOSITE HELICOPTER ROTOR HUB (CONT.)

REVISED SECTION PROPERTIES ~ SECT. B-B
(CONT.)

ITEM	A	E $\times 10^6$	AE $\times 10^6$	y	AEy $\times 10^6$	AEy² $\times 10^6$	EI₀ $\times 10^6$
1	.075	6.8	0.510	0.99	.50490	.49985	.00150
2				1.32	.67320	.88862	
3				1.64	.83640	1.37169	
4				1.96	.99960	1.95921	
5				2.27	1.15770	2.62797	
6				2.58	1.31580	3.39976	
7				2.91	1.98410	4.31873	
8				3.23	1.64730	5.32077	
9				3.53	1.80030	6.35505	
10				3.86	1.96860	7.59879	
11				4.17	2.10670	8.86833	
12	.075	6.8	0.510	4.49	2.28990	10.28165	.00150
13	0.296	4.4	1.302	0.20	0.26040	.05208	.00204
14	.819	3.5	2.867	0.14	.40138	.05619	.01779
15	.675	1.78	1.202	0.50	.60100	.30050	.00087
16	1.517	1.78	2.700	2.42	6.53400	15.81228	1.55070
17	0.621	1.78	1.105	4.33	9.78465	20.71753	.01865
18	0.220	3.5	.770	4.67	3.59590	16.79285	.00066
19	.182	4.4	.801	4.65	3.72465	17.31962	.00130
20	.296	1.78	.991	2.48	1.09368	2.71232	.25005
			17.308		37.60016	127.49877	2.86346

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COMPOSITE HELICOPTER ROTOR HUB (CONT.)

REVISED SECT. PROPERTIES ~ SECTION B-B (CONT.)

$$\bar{y} = \frac{\Sigma AEy}{\Sigma AE}$$

$$= \frac{37.80016}{17.308}$$

$$= \underline{\underline{2.184}}$$

$$\Sigma EI = 2\left[\Sigma Ay^2 + \Sigma EI_o - \bar{y}\Sigma AEy\right]$$

$$= 2\left[127.20879 + 2.86396 - 2.184(37.80016)\right] \times 10^6$$

$$= \underline{\underline{95.11 \times 10^6}}$$

$$\Sigma AE = 2\left[\Sigma AE\right]$$

$$= 2(17.308) \times 10^6$$

$$= \underline{\underline{34.62 \times 10^6}}$$

MJO NO. 3027-001	SUBJECT		DATE 7/25/72	CHECKED BY G.
TASK NO.			CALCULATIONS BY A.M.T.	SHEET NO. 115

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COMPOSITE HELICOPTER ROTOR HUB (CONT.)

REVISED X-SECTION @ SECTION A-A

COND. TW7F2
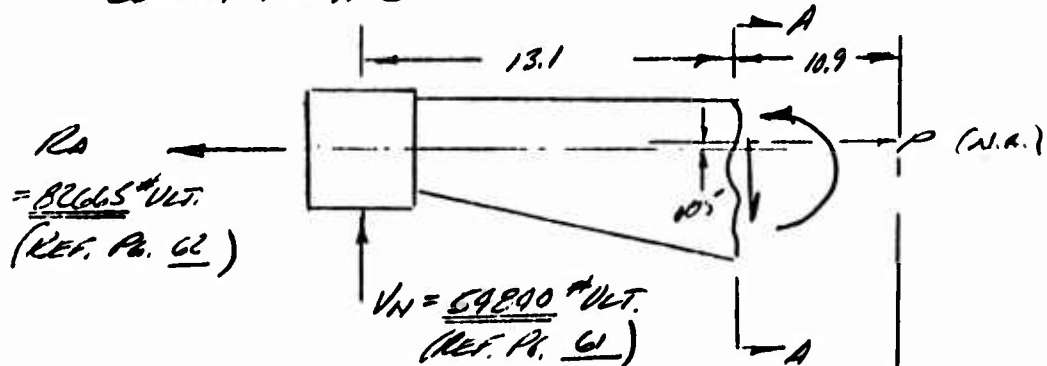
@ N.A. AT SECTION A-A

$V = V_N = \underline{59840}$ # ULT.

$M = V_N (13.1) + R_A (.05)$

$\quad = 59840 (13.1) + 82665 (.05)$

$M = \underline{788537}$ IN # ULT.

$P = R_A = \underline{82665}$ # ULT.

NONLINEAR THEORY IS USED.

MJO NO. 8027-001	SUBJECT		DATE 8/16/72	CHECKED BY
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COMPOSITE HELICOPTER ROTOR HUB (CONT.)

CONT. TW7F2
REVISED SECTION A-A
STRAIN AT YIELD FOR ITEM (16)

$$\varepsilon_{(16)} = \frac{F_{tu}}{E}$$

$$= \frac{14,400}{1.78 \times 10^6}$$

$$= 0.00808 \text{ in/in}$$

$$F_{t_{45°}} = 0.9 (16,000)$$

$$= 14,400 \text{ psi @ } 160°F$$

FOR 1543 E/EPOXY
CROSS LAMINATED
@ ±45°, REF MIL HDBK
17 [3] FIG 5.2.2

$$E = 1.78 \times 10^6$$

ABOVE THE LIMIT STRAIN LEVEL FOR ITEM (16),
E FOR ITEMS (14), (15), (16) & (20) IS ASSUMED
TO BE 0:

THEN, THE MODIFIED SECTION PROPERTIES
ARE:

ITEM	AE $\times 10^6$	AEy $\times 10^6$	AEy^2 $\times 10^6$	EI_o $\times 10^6$
Σ	24.099	55.84186	236.43363	6.95162
-14	-1.458	-0.71442	-0.35006	-0.02459
-15	-3.710	-11.24130	-34.06113	-6.62512
-16	-1.105	-6.17695	-34.52915	-0.01865
-20	-0.441	-1.09368	-2.71232	-0.22745
	17.385	36.61551	164.78077	.05581

COMPOSITE HELICOPTER ROTOR HUB (CONT.)

COND. TLU7F2

REVISED SECTION A-A (CONT.)

$$\bar{y} = \frac{\Sigma AE y}{\Sigma AE} = \frac{36.61551 \times 10^6}{17.385 \times 10^6}$$

$$= 2.106 \text{ in}$$

$$\Sigma EI_{MOD} = 2\left[\Sigma AE y^2 + \Sigma EI_0 - \bar{y} \Sigma AE y\right]$$

$$= 2\left[164.78 + 0.05 - 2.106(36.616)\right]$$

$$\Sigma EI_{MOD} = 175.43 \times 10^6$$

$$\Sigma AE_{MOD} = 2(17.385) = 34.77 \times 10^6$$

AT LIMIT STRAIN IN ITEM ⑯

$$\epsilon = .00808 = \frac{My}{\Sigma EI} + \frac{P}{\Sigma AE} \quad , \qquad P = kM$$

$$k = \frac{P}{M}$$

$$.00808 = \frac{M(3.50)}{227.99 \times 10^6} + \frac{0.1144 M}{48.20 \times 10^6} \qquad = \frac{82665}{722537}$$

$$= 0.1144$$

$$.00808 = (.01535 + .00237)10^{-6} M$$

$$M = \frac{.00808 \times 10^6}{.01772}$$

$$y_{⑯} = 3.50 \text{ (REF. Pg. 109)}$$

$$\Sigma EI = 227.99 \times 10^6 \text{ REF.}$$

$$= 455,980 \text{ in}^\# \qquad \Sigma AE = 48.20 \times 10^6 \text{ Pg. 112}$$

JO NO 3027-CU1	SUBJECT		DATE 5/16/72	CHECKED BY
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COMPOSITE HELICOPTER ROTOR HUB (CONT.)

COND. TW 7F2
REVISED SECTION A·A (CONT.)

$P = kM$

$= 0.1144 (455,980)$

$P = 52164 \#$

$\Delta M = M_{TOT} - M$

$= 722537 - 455980$

$\Delta M = 266557 \text{ in} \#$

$\Delta P = P_{TOT} - P$

$= 82665 - 52164$

$\Delta P = 30501 \#$

STRESS IN ITEM ⑯, NONLINEAR THEORY

$$f_{f} = \epsilon_{(16)} \epsilon_{(16)} = \left[\left(\frac{My}{\Sigma EI} + \frac{P}{\Sigma AE} \right) + \left(\frac{\Delta My}{\Sigma EI_{MOD}} + \frac{\Delta P}{\Sigma AE_{MOD}} \right) \right] \epsilon_{(16)}$$

$$= \left[\frac{455980(363)}{227.99 \times 10^{6}} + \frac{52164}{98.20 \times 10^{4}} + \frac{266557(363)}{175.43 \times 10^{6}} + \frac{30501}{34.7 \times 10^{4}} \right] 3.9 \times 10^{6}$$

$= 57267 \text{ psi ULT.}$

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COMPOSITE HELICOPTER ROTOR HUB (CONT.)

COND. TW7F2
REVISED SECTION A-A (CONT.)

TENSILE STRESS IN LWR PLATE (ITEM (18))

$$F_{tu} = 84,000 \, psi \, (REF. \, Pg. \, \underline{5} \,)$$

$$M.S. = \frac{F_{tu}}{f_t} - 1$$

$$= \frac{84,000}{57,467} - 1 = \text{———————} \quad \underline{+0.46}$$

COMPRESSION STRESS IN UPPER PLATE
(ITEM (13))

NONLINEAR THEORY:

$$\epsilon_{(13)} = \left(\frac{M y_c}{\Sigma EI} - \frac{P}{\Sigma AE} + \frac{\Delta M y_c}{\Sigma EI}_{MOD} - \frac{\Delta P}{\Sigma AE}_{MOD} \right),$$

$$= \frac{455,980 (2.22)}{227.99 \times 10^6} - \frac{52,164}{98.10 \times 10^6} + \frac{266,557 (2.22)}{175.43 \times 10^6} - \frac{30,501}{30.77 \times 10^6}$$

$$y_c = 2.22$$
$$(REF. \, Pg. \, 109)$$

$$= .00585 \, in/in$$

$$f_c = \epsilon E \quad, \quad E = 5.1 \times 10^6 \, psi \, (REF. \, Pg. \, \underline{2} \,)$$

$$= .00585 (5.1 \times 10^6)$$

$$f_c = \underline{29,830 \, psi} \, ULT.$$

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COMPOSITE HELICOPTER ROTOR HUB (CONT.)

COND. TW 7F2
REVISED SECTION A-A (CONT.)

COMPRESSION STRESS IN UPPER PLATE
(ITEM ㉓)

$$F_{C_{cr}} = 55,800 \, psi \quad (REF. PG. \underline{15})$$

$$M.S. = \frac{F_{C_{cr}}}{f_c} - 1$$

$$= \frac{55,800}{29,830} - 1 = \underline{\underline{+0.87}}$$

SHEAR STRESS IN ITEM ⑰:

$$\Sigma EQ = 2\left[A'E_{19} \, Y_{19} + AE_{13} \, Y_{13}\right], \quad AT \; CORNER$$

$$= 2\left[0.43(9.6)(2.18) + 9.19(2.16)\right]_{\times 10^6}$$

$$= 26.73 \times 10^6$$

$$A'_{19} = 1.6 \times .269$$
$$= 0.43 \, IN^2$$

$$\bar{E}_{19} = 9.6 \times 10^6$$
$$(REF. PG. \underline{20})$$

$$A_{13}E_{13} = 9.19 \times 10^6$$
$$(REF. PG. \underline{111})$$

$$Y_{19} = 2.18$$

$$Y_{13} = 2.16$$

COMPOSITE HELICOPTER ROTOR HUB (CONT.)

COND. TW7F2
REVISE SECTION A-A (CONT.)
SHEAR STRESS IN ITEM ⑲ (CONT.)

$$f_s = \frac{V_N \Sigma EQ}{\Sigma EIb} ,$$

$$b = 2t_{⑲}$$

$$= \frac{54,840 \, (26.73 \times 10^6)}{227.99 \times 10^6 \, (0.538)}$$

$$= 2 \, (.269)$$

$$= 0.538 \, IN$$

$$= 11,950 \, psi$$

$$\Sigma EI = 227.99 \times 10^6$$
$$(REF. \, P_6. \, \underline{113})$$

$$F_{s_{⑲}} = 14,470 \, psi \, (REF. \, P_6. \, \underline{23})$$

$$M.S. = \frac{F_s}{f_s} - 1$$

$$= \frac{14470}{11950} - 1 = \underline{\quad\quad} \, \underline{+0.21}$$

COMPOSITE HELICOPTER ROTOR HUB (CONT.)
REVISED X-SECTION AT SECTION B-B
COND. TW7F2

R_A = 82665# ULT.
(REF. P. 62)

V_N = 54840# ULT. (REF. P. 61)
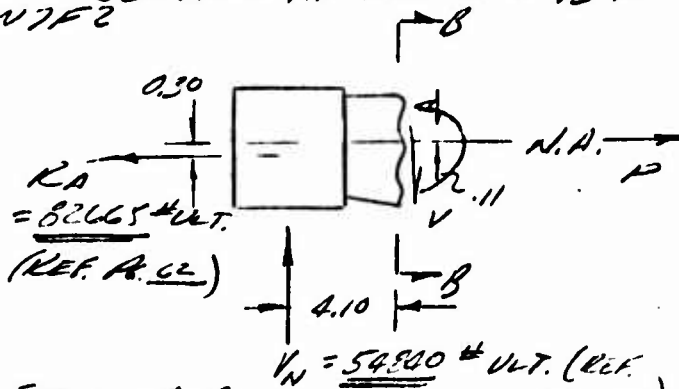
AT N.A. @ SECT B-B

$V = V_N = 54840$# ULT.

$M = V_N (4.10) + R_A (0.30)$

$= 54840 (4.10) + 82665 (0.30)$

$= 249644$ IN# ULT.

$P = R_A = 82665$# ULT.

STRAIN IN ITEM ⑰

NONLINEAR THEORY IS USED

$F_{t_{45°}} = 0.9 (16,000) = 19,400 \, psi @ 160°F$

$F_{t_{±45°}} = 16,000 \, psi @ R.T.$
1543E CROSS LAM
@ ±45° REF. N.
HUCK 17 [3] FIG 5-22

$E = 1.78 \times 10^6$

STRAIN @ YIELD

$\epsilon = \dfrac{F_t}{E} = \dfrac{19,400}{1.78 \times 10^6} = .00808 \, IN/IN$

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TASK NO.		CALCULATIONS BY H.N.T.	SHEET NO. 123

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COMPOSITE HELICOPTER ROTOR HUB (CONT.)

SECTION B-B
CONDUCTIVITE (CONT.)

ABOVE LIMIT STRAIN LEVEL FOR ITEM (1)
E FOR ITEMS (15)(16) & (17) IS ASSUMED TO
BE 0.

MODIFIED SECTION PROPERTIES:

ITEM	AE	AEy	AEy²	EI₀
Σ	17.308	37.80016	127.24879	2.86346
-15	-1.202	-.60100	-.30050	-.02027
-16	-2.700	-6.53400	+5.81228	-2.55470
-17	-1.105	-4.78965	-20.71753	-.01865
	12.301	25.88051	90.91848	.26984

$$\bar{y} = \frac{\Sigma AEy}{\Sigma AE} = \frac{25.88051}{12.301} = 2.104$$

$$\Sigma EI_{MOD} = 2\left[\Sigma AEy^2 + \Sigma EI_0 - \bar{y}\Sigma AEy\right]$$

$$= 2\left[90.91848 + 0.26984 - 2.104(25.88051)\right] \times 10^6$$

$$= 72.47 \times 10^6$$

$$\Sigma AE_{MOD} = 2\left[\Sigma AE\right] = 2(12.301)\times 10^6$$

$$= 24.602 \times 10^6$$

IJO NO	SUBJECT		DATE 7/../72	CHECKED BY S.
ASK NO			CALCULATIONS BY A.M.T.	SHEET NO. 124

COMPOSITE HELICOPTER ROTOR HUB (CONT.)

COND. TW 7F2 (CONT.)

SECTION B-B

FOR ITEM ⑰ @ LIMIT STRAIN

$$\epsilon = 0.00808 = \frac{My}{\Sigma EI} + \frac{P}{\Sigma AE}$$

$$.00808 = \frac{M(2.38)}{95.11 \times 10^6} + \frac{0.331(M)}{34.62 \times 10^6}$$

$$M = \frac{.00808}{.0346 \times 10^{-6}}$$

$$= 233500 \text{ IN}^{\#} @ \text{ LIMIT}$$
$$\text{STRAIN}$$
$$\text{IN } ⑰)$$

$$P = kM$$
$$= 0.331(233500)$$
$$= 77,300^{\#}$$

$$\Delta M = M_{TOT} - M$$
$$= 249,644 - 233500$$
$$= 16144$$

$$\Delta P = P_{TOT} - P$$
$$= 82665 - 77300$$
$$= 5365^{\#}$$

$$P = kM$$

$$k = \frac{P}{M}$$
$$= \frac{82665}{249644}$$
$$= 0.331$$

$$y_{17} = 2.38 \text{ IN } \left(\begin{array}{c} REF. \\ PG. \underline{\quad} \end{array} \right)$$

$$\Sigma EI = 95.11 \times 10^6 \left. \begin{array}{c} \\ \end{array} \right\} \begin{array}{c} REF. \\ P. \underline{\quad} \end{array}$$
$$\Sigma AE = 34.62 \times 10^6$$

$$\Sigma EI_{MIN} = 72.47 \times 10^6 \left. \begin{array}{c} \\ \end{array} \right\} \begin{array}{c} REF. \\ P. \underline{\quad} \end{array}$$
$$\Sigma AE_{MIN} = 24.602 \times 10^6$$

IJO NO	SUBJECT	DATE 7/25/72	CHECKED BY 9
ASK NO		CALCULATIONS BY A.W.T.	SHEET NO. 125

COMPOSITE HELICOPTER ROTOR HUB (CONT.)

COND TW 7F2

SECTION B-B

STRAIN IN ITEM (18) (NONLINEAR THEORY)

$$ \epsilon = \left(\frac{My}{\Sigma EI} + \frac{P}{\Sigma AE} \right) + \left(\frac{\Delta My}{\Sigma EI}_{MOD} + \frac{\Delta P}{\Sigma AE}_{MOD} \right), \, y_{18} = 2.53 \text{ (REF. P. 113)} $$

$$ = \left[\frac{233500(2.53)}{95.11 \times 10^6} + \frac{77300}{34.06 \times 10^6} \right] + \left[\frac{16144(2.53)}{72.4 \times 10^6} + \frac{5365}{24.602 \times 10^6} \right] $$

$$ = 0.00844 + 0.00078 $$

$$ \epsilon = .00922 \text{ IN/IN @ ULT.} $$

STRESS IN ITEM (18)

$$ f_t = \epsilon E $$

$$ = .00922 (3.5 \times 10^6) $$

$$ = 32,270 \text{ PSI} $$

$$ F_{tu_{(18)}} = 69,800 \text{ PSI (REF. P. 43)} $$

$$ M.S. = \frac{F_{tu}}{f_t} - 1 $$

$$ = \frac{69,800}{32270} - 1 = \text{———— —— —— } +1.16 $$

4JO NO	SUBJECT	DATE 7/5/72	CHECKED BY
TASK NO		CALCULATIONS BY A.M.T.	SHEET NO. 126

COMPOSITE HELICOPTER ROTOR HUB (CONT.)

SECTION B-B
COND. TW7F2
SHEAR STRESS~

V = 54840 # ULT. (REF. PG. 183)

ASSUME ENTIRE SHEAR CARRIED BY
"BASKET" (ITEMS ⑮, ⑯ & ⑰)

⑱ N.A.

ITEM	A	E	AE	y	AEy
1	.075	6.8	0.510	1.18	.602
2	↓	↓	↓	1.86	.949
3				.54	.275
4	.075	6.8	0.510	.22	.112
13	0.296	4.4	1.302	1.98	2.578
14	0.819	3.5	2.867	2.03	5.820
15	0.675	1.78	1.202	1.67	2.007
16'	0.662	1.78	1.178	0.73	0.860
20'	0.094	1.78	0.167	0.47	0.078
					13.281

$$\Sigma EQ_{N.A.} = 2 (13.281) \times 10^6$$

$$= 26.562 \times 10^6$$

IO NO 3027-001	SUBJECT	DATE 7/27/72	CHECKED BY 11
SK NO.		CALCULATIONS BY A.M.T.	SHEET NO. 127

<u>COMPOSITE HELICOPTER ROTOR HUB (CONT.)</u>

SECTION B-B
COND. TW7F2
SHEAR STRESS (CONT.)

$$f_s = \frac{V_N \Sigma EQ}{\Sigma EI b}$$

$$= \frac{54840\,(26.562 \times 10^6)}{95.11 \times 10^6 (1.098)}$$

$$= 13949 \text{ psi ULT.}$$

$V_N = 54840$ # ULT.

$\Sigma EI = 95.11 \times 10^6$ (REF. Pg. 115)

$b = 2(.45 + .099)$

$\quad = 1.098$ IN

$\Sigma EQ = 26.562 \times 10^6$ (REF. Pg. 122)

$F_{SU} = 26,000\,(0.9)$

$\quad = 23,400$ psi @ 160°F

(1543/EPOXY @ 95°
REF. MIL HDBK 17 [3] FIG
5-58)

$$M.S. = \frac{F_{SU}}{f_s} - 1$$

$$= \frac{23400}{13949} - 1 = \text{———— ———— ————} \quad \underline{+0.68}$$

MJO NO. 3027-001	SUBJECT		DATE 7/28/72	CHECKED BY 12
TASK NO			CALCULATIONS BY A.M.T.	SHEET NO. 128

COMPOSITE HELICOPTER ROTOR HUB (CONT.)

FATIGUE STRESS IN SHEAR AT SECTION B·B
(SEE SKETCH, PG. 113, ITEM 16 AT N.A.)

FOR CRUISE CONDITION FATIGUE (LOW STRESS/
HIGH CYCLE FATIGUE LOADING)
FOR CYCLE MAXIMUM LOADS~

$V_{N_{MAX}}$ = 17257 LBS LIMIT (REF. PG. 69)

@ N.A. IN ITEM 16,
BY RATIO:

$$f_{S_{MAX}} = \frac{V_{N_{MAX}}}{V_{N_{COND TW7F2}}} \left(f_{S_{COND TW7F2}} \right)$$

$V_{N_{COND TW7F2}}$ = 54840 ULT. (REF. PG. 128)

$f_{S_{COND TW7F2}}$ = 13949 PSI ULT. (REF. PG. 128);

$$= \frac{17257}{54840} (13949)$$

$$= 4389 PSI$$

FOR CYCLE MINIMUM LOADS~

$V_{N_{MIN}}$ = -5790 LBS. LIMIT (REF. PG. 69)

$$f_{S_{MIN}} = \frac{V_{N_{MIN}}}{V_{N_{COND TW7F2}}} \left(f_{S_{COND TW7F2}} \right)$$

$$= \frac{-5790}{54840} (13949) = -1473 PSI$$

JO NO.	SUBJECT	DATE 7/25/7:	CHECKED BY 13
TASK NO.		CALCULATIONS BY A. M. S	SHEET NO. 129

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COMPOSITE HELICOPTER ROTOR HUB (CONT.)

FATIGUE STRESS IN SHEAR AT SECT. B-B
CRUISE CONDITION (CONT.) IN ITEM (16) ④ N.A.

SUMMARY ~

$$f_{s_{MAX}} = 4389 \, psi$$

$$f_{s_{MIN}} = -1473 \, psi$$

$$f_{s_{MEAN}} = 1458 \, psi$$

$$f_{s_{ALT}} = 2931 \, psi$$

$$R = \frac{f_{s_{MIN}}}{f_{s_{MAX}}} = \frac{-1473}{4389} = -0.336$$

JOB NO.	SUBJECT		DATE 7/31/7	CHECKED BY K
TASK NO.			CALCULATIONS BY A.M.T.	SHEET NO. 130

COMPOSITE HELICOPTER ROTOR HUB ~ (CONT.)

FATIGUE STRESS IN SHEAR AT SECTION B-B

FOR "GAG" CONDITION (LOW CYCLE -
HIGH STRESS)

$V_{MAX} = 2 (18280) = 36560$ # (REF. STATIC AND

FATIGUE TEST PROGRAM PLAN
REPORT NO. SOE-72-9, [15] PG. 2)

BY RATIO:

$f_{S_{MAX}} = \dfrac{V_{MAX}}{V_{TW7FL}} (f_{S_{TW7FL}})$, $V_{TW7FL} = 59840$ #
(REF. PG. 123)

$= \dfrac{36560}{59840} (13949)$ $f_{S_{TW7FL}} = 13949 psi$
(REF. PG. 128)

$= 9300 psi$

$V_{MIN} = 0$

$f_{S_{MIN}} = 0$

$f_{S_{ALT}} = \dfrac{9300}{2} = 4650 psi$

$f_{S_{MEAN}} = 4650 psi$

$R = \dfrac{f_{S_{MIN}}}{f_{S_{MAX}}} = \dfrac{0}{9300} = 0$

JO NO. 3027-001	SUBJECT		DATE 6/12/72	CHECKED BY
TASK NO.			CALCULATIONS BY A.N.T.	SHEET NO. 131

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COMPOSITE HELICOPTER ROTOR HUB ~ (CONT.)

FATIGUE ALLOWABLE STRESSES ~

A NON-DIMENSIONAL CONSTANT LIFE
FATIGUE DIAGRAM FOR 1543 E GLASS/EPOXY
LAMINATES, CROSS-LAMINATED, LOADED IN
SHEAR AT ±45° TO WARP IS CONSTRUCTED
FROM DATA IN USAAVLABS TECH. REPT. [11]
69-9, TABLE $\overline{XIII}$. A WORKING GOODMAN
DIAGRAM IS THEN DRAWN USING A REDUCTION
FACTOR OF 0.5 FOR VALUES OF $F_{s_{ALT.}}$ AT
R = -1.0. S/N DIAGRAMS ARE DRAWN AND
FAILURE INITIATION TIMES ARE CALCULATED
USING ALLOWABLE STRESS WITH & WITHOUT
THE 0.5 REDUCTION FACTOR.

4JO NO 3027-001	SUBJECT	DATE 8/18/72	CHECKED BY
ASK NO		CALCULATIONS BY A.M.T.	SHEET NO. 132
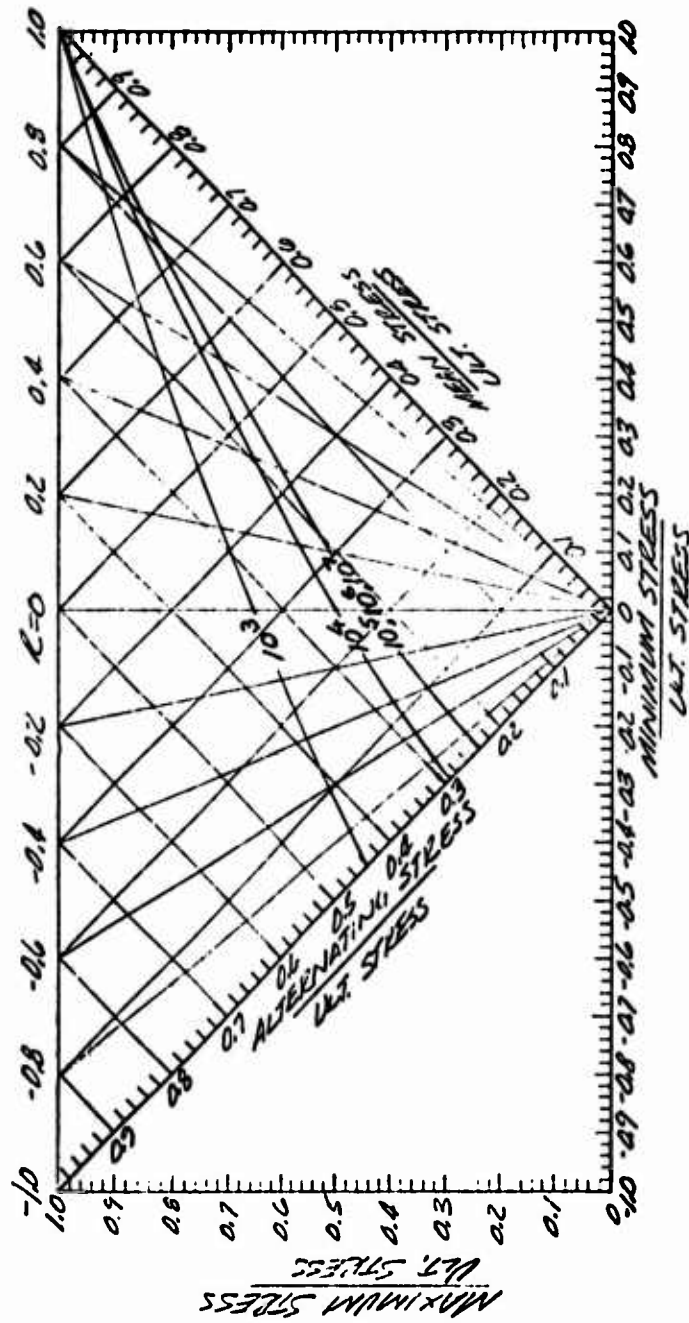
Figure 51. Nondimensional Constant Life Fatigue Diagram Based on
Average Values at R = 1.0 for BP 907-1435 Glass Cloth
Loaded in Shear at ± 45° to Warp.

207
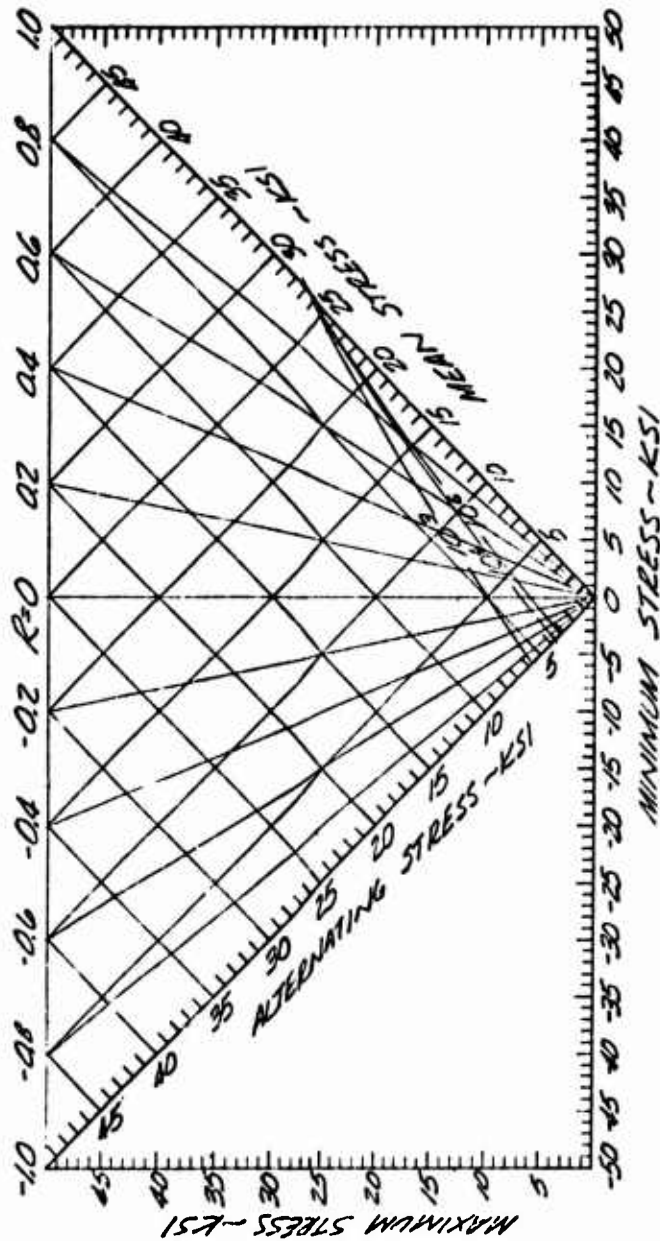
Figure 52. Working Goodman Fatigue Diagram for Cross-Laminated
1543 E-Glass/Epoxy Laminate in Shear at ± 45° to Warp
(0.5 Reduction Factor Applied to Average Values of
Alternating Stress at R = 1.0).

208
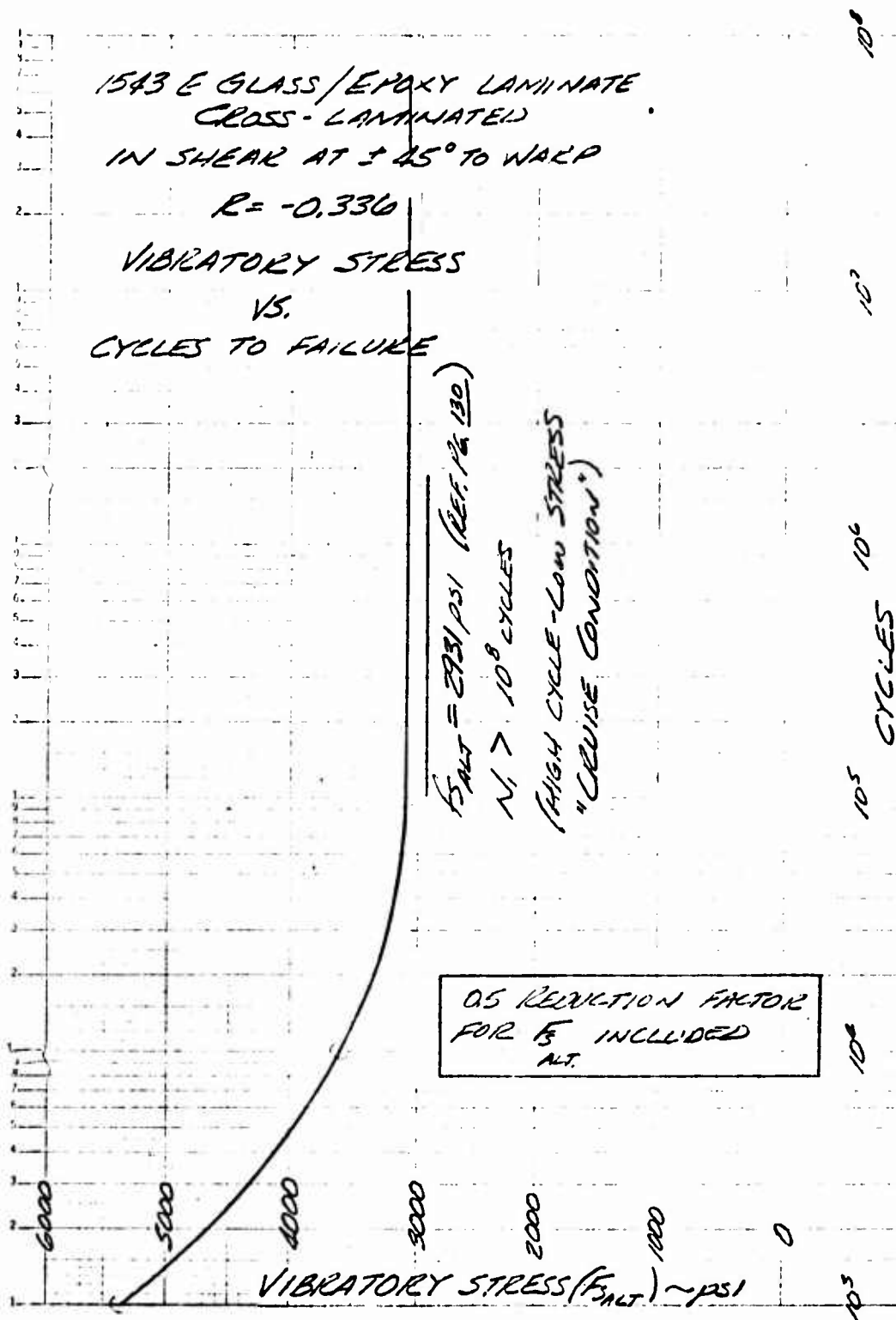
Figure 53. 1543 E-Glass/Epoxy Laminate Cross-Laminated in Shear at ± 45°
to Warp, R = 0.336, Vibratory Stress Vs. Cycles to Failure.

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COMPOSITE HELICOPTER ROTOR HUB ~ (CONT.)

FAILURE INITIATION TIME FOR SHEAR
FATIGUE STRESS IN ITEM (16) AT SECT. B-B

HIGH CYCLE - LOW STRESS, "CRUISE CONDITION".

ALLOWABLE CYCLES WITH O.S REDUCTION
FACTOR INCLUDED ~

FOR $R = -0.336$ } (REF. PG. 130)
& $f_{S_{ALT}} = 2921$ PSI

$N_1 > 10^8$ CYCLES (REF. PG. 135)

APPLIED ALTERNATING STRESS IS
LESS THAN THE ENDURANCE LIMIT
OF THE MATERIALS AND THE HUB
WEB IS UNDAMAGED FOR THE
HIGH CYCLE - LOW STRESS "CRUISE
CONDITION" SHEAR FATIGUE STRESS
REGIME.

IF THE O.S REDUCTION FACTOR IS
NOT INCLUDED, THIS FATIGUE STRESS IS
NOT CRITICAL BY INSPECTION.

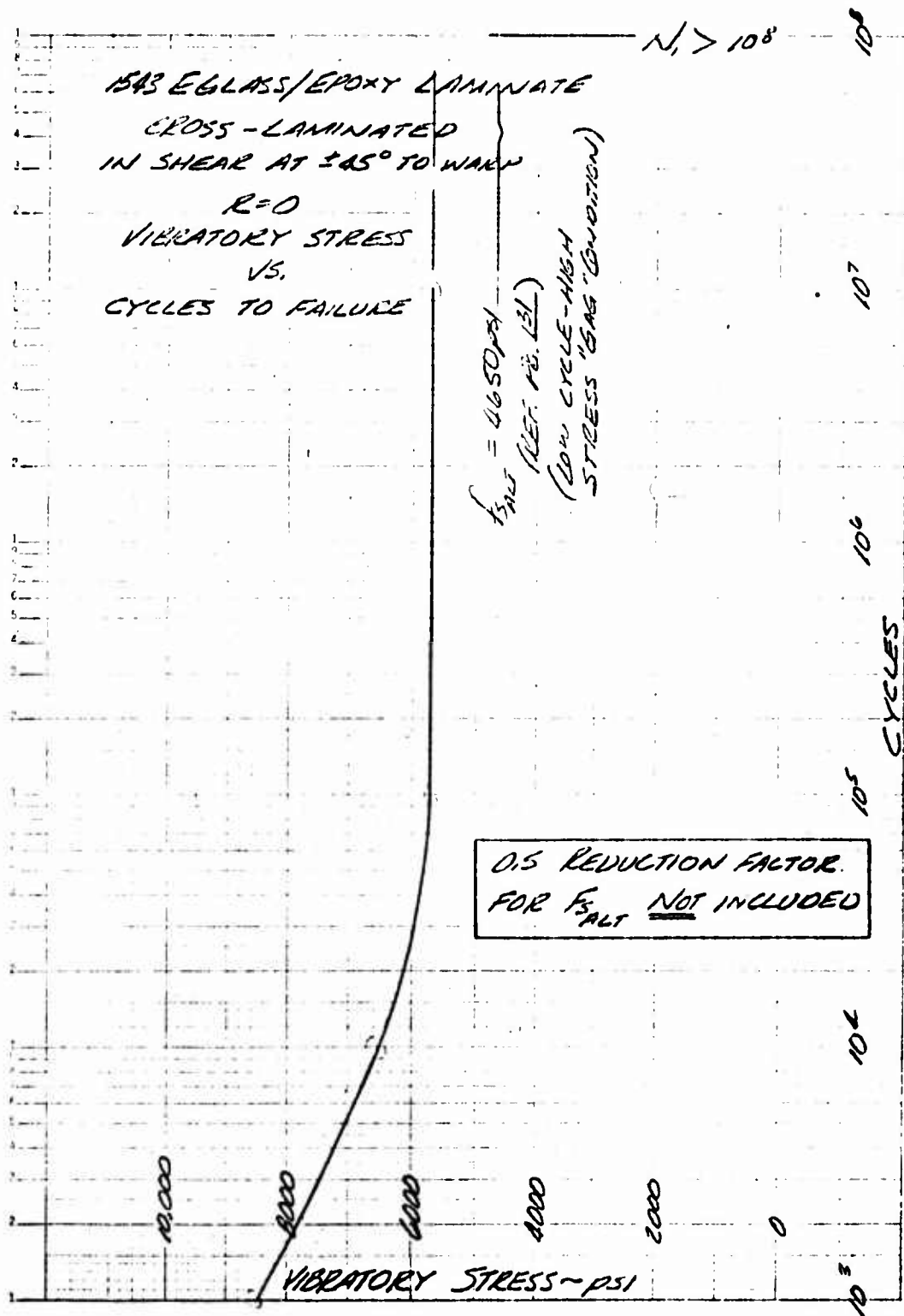| MJO NO 5027-001	SUBJECT	DATE 8/18/72	CHECKED BY
TASK NO		CALCULATIONS BY A.M.T.	SHEET NO. 136

210
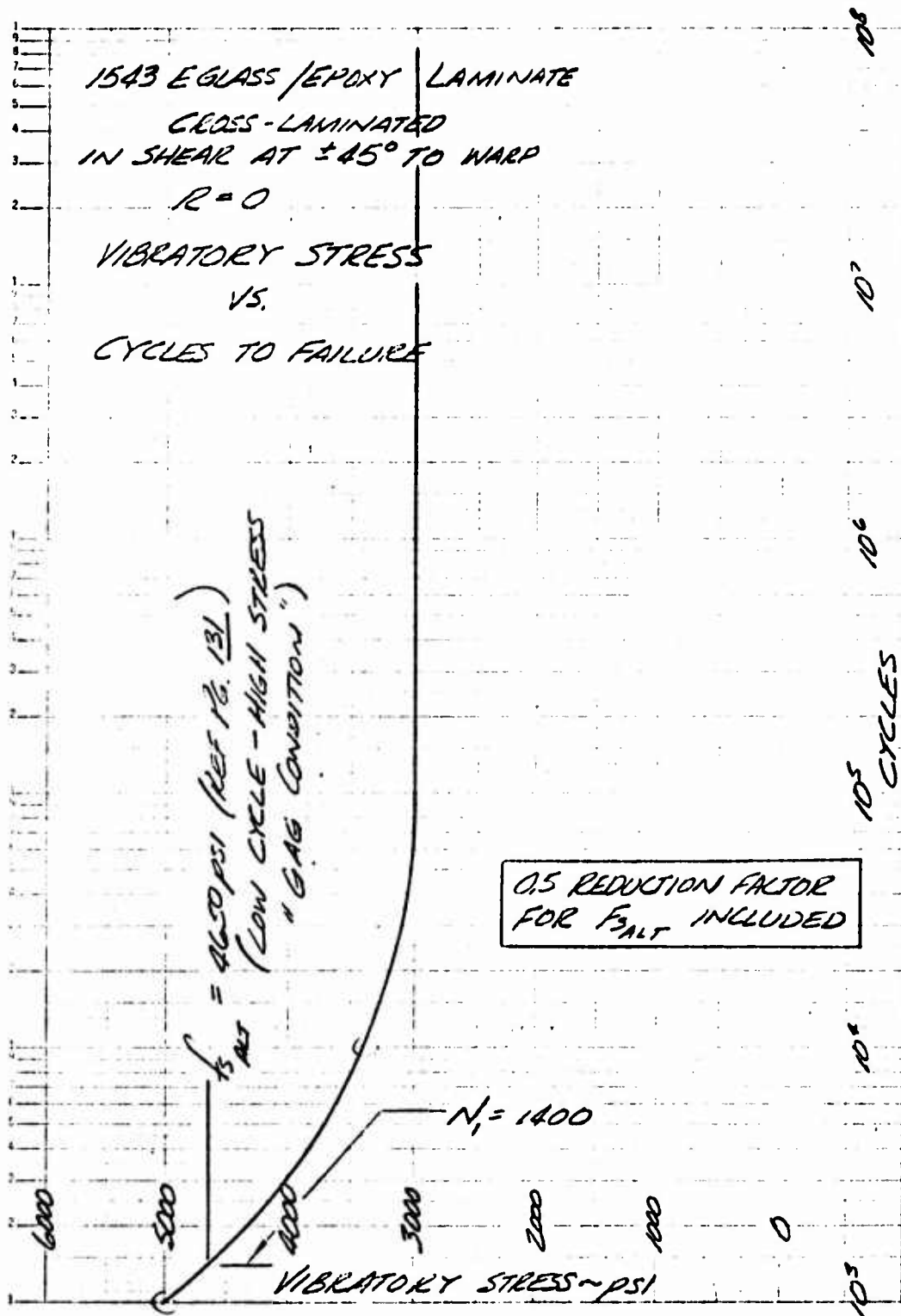
Figure 54. 1543 E-Glass/Epoxy Laminate Cross-Laminated in Shear at ± 45° to Warp, R = 0, Vibratory Stress Vs. Cycles to Failure (0.5 Reduction Factor for Fsalt Included).

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COMPOSITE HELICOPTER ROTOR HUB — (CONT.)

FAILURE INITIATION TIME FOR SHEAR
FATIGUE STRESS IN ITEM ⑯ AT SECTION
B-B.

LOW CYCLE - HIGH STRESS, "GAG CONDITION".

ALLOWABLE CYCLES WITH 0.5 REDUCTION
FACTOR INCLUDED ~

$$\left. \begin{array}{l} \text{FOR } R = 0 \\[2mm] \text{\&} \quad f_{S_{ATT}} = 4650 \, psi \end{array} \right\} \text{(REF. Pg. } \underline{131} \text{)}$$

$$N_1 = 1400 \text{ CYCLES (REF. Pg. } \underline{137} \text{)}$$

APPLIED CYCLES PER 100 FLIGHT HRS. ~

ASSUME:

$$n_1 = 214 + 24 = 238 \text{ OCCURANCES/100 HRS.}$$

(REF. SIKORSKY AIRCRAFT REPT.
SER-64515, [16] PG 514)

$$\underline{\text{DAMAGE}/100 \text{ HRS}} = \frac{n_1}{N_1} = \frac{238}{1400} = 0.170$$

$$\underline{\text{FAILURE INITIATION TIME}} = \frac{100}{\text{DAM }/100 \text{ HRS}}$$
$$= \frac{100}{0.1} =$$

Figure 55. 1543 E-Glass/Epoxy Laminate Cross-Laminated in Shear at $\pm 45^\circ$ to Warp, R = 0, Vibratory Stress Vs. Cycles to Failure (0.5 Reduction Factor for Fs$_{alt}$ Not Included).

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COMPOSITE HELICOPTER ROTOR HUB (CONT.)

FAILURE INITIATION TIME FOR SHEAR
FATIGUE STRESS IN ITEM (16) AT
SECTION B-B.

LOW CYCLE - HIGH STRESS, "GAG CONDITION".

<u>ALLOWABLE CYCLES WITH 0.5 REDUCTION</u>
<u>FACTOR <u>NOT</u> INCLUDED</u> ~

$$FOR \quad R = 0$$
$$\& \quad f_{S_{ALT}} = 4650 \, psi \Big\} (REF. \, Pg. \, \underline{131})$$

$$N_1 > 10^8 \, (REF. \, Pg. \, \underline{139})$$

APPLIED ALTERNATING STRESS IS
LESS THAN THE ENDURANCE LIMIT
OF THE MATERIALS AND THE HUB
WEB IS UNDAMAGED FOR THE LOW
CYCLE - HIGH STRESS "GAG CONDITION"
SHEAR FATIGUE STRESS REGIME.

MJO NO. 3027-001	SUBJECT		DATE 8/18/72	CHECKED BY
TASK NO			CALCULATIONS BY A.M.T	SHEET NO. 140

COMPOSITE HELICOPTER ROTOR HUB (CONT.)

REVISED ATTACHMENT ~
LOWER PLATE TO BASKET @ SECTION A-A

$$q = \frac{V\Sigma\Sigma Q}{2\Sigma\Sigma I}$$

$\Sigma\Sigma I = 227.99 \times 10^6$
(REF. PG 112)

$$= \frac{54,840(24.15 \times 10^6)}{2(227.99 \times 10^6)}$$

$\Sigma\Sigma Q$ FOR ITEM ⑬ & ⑱
SEE SKETCH PG. 109

$q = 2904$ #/IN ULT.

$$\Sigma\Sigma Q = 2\left[AE y_{⑬} + AE y_{⑱}\right]$$

TRY AN 174 BOLT &
NEGLECT BOND STRENGTH
SINGLE SHEAR STRENGTH

$y_{⑬} = 5.95 - 2.317$
$= 3.63$ IN

$y_{⑱} = 5.88 - 2.317$

$P_{ALLOW} = 3680$ # ULT. (REF. MIL HDBK 5 [6] $= 3.56$ IN
        TABLE 8.1.2(a)
        CLASS S-3)

$AE_{⑬} = 1.555$ ⎰ REF.
$AE_{⑱} = 1.806$ ⎱ PG 111

SPACING = 1.063 IN

FASTNER LOAD ~

$$\Sigma\Sigma Q = 2\left[(1.555)3.63 + 1.806(3.56)\right]$$

$$P_{bar} = qS$$
$$= 2904(1.063)$$
$$= 3087 \text{ #/BOLT}$$

$$= 24.15 \times 10^6$$

MJO NO	SUBJECT		DATE 1/30/72	CHECKED BY
TASK NO			CALCULATIONS BY A.M.J.	SHEET NO. 141

COMPOSITE HELICOPTER ROTOR HUB (CONT.)

REVISED ATTACHMENT ~ LOWER PLATE TO BASKET (CONT.)

FOR AN 174 BOLTS IN SHEAR:

$$M.S. = \frac{P_{ALLOW}}{P_{BOLT}} - 1$$

$$= \frac{3680}{3087} - 1 = \underline{\qquad \qquad +0.19}$$

BEARING STRESS IN BASKET ~

$$f_{br} = \frac{P_{BOLT}}{Dt}$$

$$= \frac{3087}{0.25(.45)}$$

$$f_{br} = 27,440 \, psi$$

$$F_{br} = 32,000 \, psi \; (REF: \; MIL \; HDBK \; 17, \; [3] \; TABLE \; 2-7)$$

$$M.S. = \frac{F_{br}}{f_{br}} - 1$$

$$= \frac{32,000}{27,440} - 1 = \underline{\qquad \qquad +0.17}$$

MJO NO	SUBJECT	DATE 1/3/72	CHECKED BY
TASK NO		CALCULATIONS BY A.N.T.	SHEET NO 142

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COMPOSITE HELICOPTER ROTOR HUB (CONT.)

REVISED ATTACHMENT~ LOWER PLATE TO
BASKET (CONT.)

ADD 2021-T4 AL ALY DOUBLER TO
LOWER PLATE~

$$f_{br_n} = \frac{P_{BLT}\, E_n}{D\, \Sigma t E}$$

$$f_{br_n} = \frac{3087\, E_n}{.250(.230 \times 5.4 + .125(1.5)) 10^6}$$

$$= 4834 \times 10^{-6} (E_n)$$

IN AL ALY DOUBLER

$$f_{br}_{AL\,ALY} = 4834 \times 10^{-6} (10.5 \times 10^6)$$

$$= 50756\ psi$$

$$F_{bru} = 118,000\ psi\ (e/D = 2.0)$$

M.S. ~ HIGH

IN ITEM (1) LAMINATE

$$f_{br} = 4834 \times 10^{-6} (5.4 \times 10^6)$$

$$= 26100\ psi\ ULT.$$
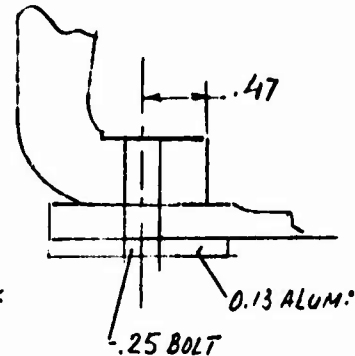
FOR O COND $F_{bru} = 50000$
$F_{bry} = 19000$

M.S. - NEG DO NOT USE
O COND MATL

MJO NO	SUBJECT	DATE 8/30/72	CHECKED BY
TASK NO		CALCULATIONS BY A.M.T.	SHEET NO. 143

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COMPOSITE HELICOPTER ROTOR HUB (cont.)

REVISED ATTACHMENT ~ LOWER PLATE
TO BASKET (CONT.)

BEARING STRESS IN ITEM ③ (CONT)

$F_{br} = 32,000$ psi

$M.S. = \dfrac{F_{br}}{f_{br}} - 1$

$= \dfrac{32,000}{26104} - 1 = $ ———   ——— $+0.22$

SHEAR STRESS — AL ALY DOUBLER TO
ITEM ①

$f_s = \dfrac{V}{A}$

$= \dfrac{3097}{1.003(1.5) - \dfrac{\pi(.25)}{4}}$

$= 1975$ psi

MJO NO	SUBJECT		DATE 8/30/72	CHECKED BY
TASK NO			CALCULATIONS BY A.M.T.	SHEET NO. 144

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Figure 56. Rotor Hub Assembly
(WRD Drawing No. 4670,
Sheet No. 1).

PLAN VIEW

O) ASSY

PLAN VIEW

ARM INDEX NUMBER DIAGRAM

NOTES: UNLESS OTHERWISE SPECIFIED

1. DO NOT SCALE DRAWING. WORK TO DIMENSIONS GIVEN
2. DIMENSIONS MARKED "BASIC" LOCATE THE TRUE POSITION AND CARRY NO TOLERANCES
3. DRAWING INTERPRETATION PER MIL-D-1000

4. MATERIAL - E-GLASS SCOTCHPLY XP 2513 AND NARMCO 507, 1581 STYLE. LAY-UP SEQUENCE, NUMBER OF PLIES AND FIBER ORIENTATION TO BE AS SHOWN IN SCHEMATIC DIAGRAMS ON SHT 2 (ZONES ...)

5. MATERIAL FOR -7 & -8 - S-GLASS SCOTCHPLY XP 2513, NUMBER OF PLIES AND FIBER ORIENTATION AS SHOWN IN DIAGRAM ON SHT 1 (ZONE ...)

6. APPLY EA 934 ADHESIVE AS FOLLOWS:

C. BETWEEN 4672 LUG INSERT AND LAMINATED STRUCTURE

E. TO FAYING SURFACES OF 4679 AND 4672 & LAMINATED STRUCTURE

7. EA 934 ADHESIVE MAY BE PURCHASED FROM DEXTER - HYSOL, LOS ANGELES

8. ADD (11) ADDITIONAL PLIES OF NARMCO 507, ISSUE STYLE IN THIS AREA (ZONES ...) FIBER ORIENTATION TO BE ±45°

9. ...

10. CALCULATED WEIGHT FOR -0 ASSY

12. ...

13. LAY UP SCHEDULE - ADJACENT PLIES SHALL HAVE WARP FIBERS IN ALTERNATING PLUS(+) AND MINUS(-) 45° DIRECTION

Figure 56 - Continued
(WRD Drawing No. 4670,
Sheet No. 2).

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This is an engineering drawing containing multiple technical sections including fiber lay-up schematics and cross-sectional views.

SECTION G-G
FIBER LAY-UP SCHEMATIC

SECTION F-F
FIBER LAY-UP SCHEMATIC

SECTION H-H
FIBER LAY-UP SCHEMATIC

LEGEND

DETAIL J

SECTION D-D

SECTION A-A

DETAIL J

SECTION A-A

SECTION **C · C**
ROTATED 60° CLOCKWISE

SECTION **B · B**
ROTATED 60° COUNTER CLOCKWISE

Figure 56 - Continued
(WRD Drawing No. 4670,
Sheet No. 3).

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SECTION 13 - 13
ROTATED 60° COUNTER CLOCKWISE

4670,

Figure 57. Hub Main Bearing
(WRD Drawing No. 4671).

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HORN - FAR SIDE

11 875
DIA

12 250
DIA

11 015
11 010
DIA

8 685 GAGE
DIA BASIC

B 406 DIA REF
TO THEORETICAL
SHARP CORNER

DO NOT
COAT

BREAK EDGE

AN 509-516 R 7 XREA
(2) REQD

DO NOT COAT

DO NOT COAT

5 000

11 530

13 400

SECTION A-A

FILL R
DO NOT COAT

Figure 58.   Laminate Assembly
(WRD Drawing No. 4673).

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DIES TO BE MACHINED
FINAL ASSEMBLY

NOTES

1   DO NO SCALE DRAWING WORK TO DIMENSIONS GIVEN

2   DRAWING INTERPRETATION PER MIL-D-1000

3   BREAK SHARP CORNERS ON -1 & -2 .005 - .015 R

4   DIMENSIONS MARKED 'BASIC' LOCATE THE TRUE
     POSITION AND CARRY NO TOLERANCES

Figure 59.   Plate, Lower
(WRD Drawing No. 4674).

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SECTION C-C
SCALE

VIEW D-D
SCALE

SECTION D-D
SCALE

3. MATERIAL - S-GLASS SCOTCHPLY XP 2515 AND NARMCO 507, 1581 STYLE
   FIBER ORIENTATION AND LAY UP SEQUENCE TO BE AS SHOWN IN SCHEMATICS

Figure 60. Spacer, Laminate
(WRD Drawing No. 4675).

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SECTION E-E

SECTION C-C

1.65

.53

1.50 R
(4) PLACES

C

C

4.25

4.05

2.78

€ SYM
(EXCEPT AS SHOWN)

B

A

TYP

.09 R TYP

D

D

LT

SECTION D-D

SECTION B-B

).